Transfunctional Living Walls—Designing Living Walls for Environmental and Social Benefits

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Abstract

As the global urbanisation trend propels the search for a more sustainable urbanism, attention is directed towards incorporating greenery into the built environment, and the budding technology of living walls consequently receives ever more attention. Some research demonstrates the multitude of benefits of living walls, but none links this recently acquired knowledge to design imperatives.

The premise of this research was that living walls have the potential to contribute to urban sustainability, and that challenges can be resolved through design and not only through technology. Thus the aim of the work was to optimise living wall design solutions for positive social and environmental impacts. For this, a key concept was *living wall dynamics*, defined as the relationship between living walls' design and their performance. This work had three objectives: to assess possible designs and performance aspects of living walls, to identify patterns in living wall dynamics, and then to develop a theoretical basis that supports the design of living walls to enhance both social and natural capital.

Since it is not possible to arrive at a complete, detailed description of living walls, owing to their complexity, the importance of subjective knowledge, and the problems inherent in measuring living walls' sustainability, this research concentrated on holistically understanding living wall dynamics. The research problem was constructed as a performance-based design inquiry, and parametric thinking was chosen to induce generalisations regarding the influence various design and context parameters would have on living walls' performance. The research focused on external living walls, located in Tel-Aviv, on a domestic and single-building scale.

The specific research questions were formulated to address particular knowledge gaps that were identified via literature review. They were concerned with using living walls for urban agriculture, the ability of living walls to improve human wellbeing, and their ability to reduce buildings' energy consumption. The parametric approach employed three

methods to cover the related design parameters and performance aspects: case studies of domestic food-producing living walls, an online survey of living wall users, and computer simulations of living walls' thermal performance.

The results showed that a domestic living wall was able to produce considerable harvest (up to 1 kg per month per m^2 of vertical area), that it was feasible to design it to be water efficient, convenient for setup and use, and to have low embodied energy. Significant design parameters for a food-producing living wall were: available root volume, choice of plants, material and manufacturing choices, and the height of the living wall. The survey found that living wall users were highly satisfied with their living walls, especially with their social benefits (e.g. 'relaxing and mood improving' and 'educational'). In this regard, noteworthy design parameters were the size of the living wall and its location. The thermal simulation results demonstrated that living walls could significantly reduce annual building cooling energy requirements in both Tel-Aviv and Brisbane (by up to 28.8% and 16% respectively). For cooling benefits, the most significant design parameters were living wall orientation, growing substrate characteristics, irrigation, and choice of vegetation (primarily LAI).

In terms of methodology, this work established that a parametric approach can produce valuable knowledge about living wall dynamics, and can inspire future parameter-based design research. This work expanded the body of knowledge related to living walls by mapping the living wall design parameters and performance parameters, resulting in a parametric model of living walls. It demonstrated that the design space for living walls is broader than the technology-oriented discourse that was the current state-of-the-art. The findings also yielded a functional typology of living walls, patterns in living wall dynamics, and ideal living wall types. Together with the parametric model, these form a theoretical basis to support a function-based design process of *transfunctional* living walls.

Transfunctional living walls are first and foremost living walls designed according to their desired functions. In addition, they fulfil multifaceted environmental and social purposes, creating a synergy of functions spanning different aspects of performance. The concept of transfunctional living walls is useful for living wall design professionals as well as developers, builders, and policy makers. The new theoretical basis has the power to transform the design process of living walls, from a technical-oriented and aesthetically-led process to one that is function-based and holistic, guided by higher environmental and social goals.

Key Words

Green Building

Green Facades

Industrial Design

Landscape Architecture

Living Wall Design

Living Walls

Parametric Study

Sustainable Design

Vertical Vegetation

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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: March 2016

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1 Introduction

1.1 Research Topic and Significance

From an environmental point of view, living walls introduce greenery into modern cities, as do more established strategies such as green corridors, urban parks, and even green roofs (Loh & Stav, 2008). It is estimated that available vertical growing areas in inner cities in Europe equal roughly double the amount of ground area (Kohler, 2006); living walls — even more than green roofs — can thus introduce vegetation into urban areas without compromising urban density and without sacrificing expensive urban space that could otherwise be utilised for human-centred uses (e.g., rooftops can function as patio space, gardens, play areas, etc.). In summary, living walls are highly relevant due to widespread urbanisation trends and the search for better models for a sustainable urban form (Burton, Jenks, & Williams, 2013).

Although traditional living walls (i.e., climbers growing directly on a building's facade) have long been part of the urban landscape, newer technologies that allow the growth of vertical vegetation next to building walls have recently been developed (Bartczak, Dunbar, & Bohren, 2013). Studies of these technologies are fairly limited (Kohler, 2008), but academic research is gaining momentum as commercial applications become more frequent and market interest increases (Hopkins & Goodwin, 2011).

This work’s research approach evolved from a design-oriented departure point, but it also engages architectural science and social science methods. The marriage of a parametric approach originating from the exact sciences with a design approach is unique, and this combination of approaches expands upon new methodological knowledge in design research.

There is as yet no consensus regarding best practices for designing sustainable living walls, but they will eventually emerge from studies carried out by a variety of researchers and practitioners. This study delineates potential principles for their design, thus contributing to our understanding of the environmental and social impacts of living walls in cities.

1.1.1 Motivation

The topic of living walls has been the centre of my work for the past decade, both as a design professional and as an academic. Lush living walls, with their promise of integrating cities worldwide with living eco-systems, fascinated me. As an environmental activist seeking to generate positive change to our vision of future cities, I asked questions regarding what role living walls might play in that process. In asking these questions, I had to also address the feasibility of the process of greening the walls of the urban built environment. This chapter introduces the background to the topic of living walls, presents the departure points for the research, and outlines the construction of the research aim and questions.

1.2 Living Walls to Enhance Urban Sustainability

1.2.1 The promise of urban vertical surfaces

As world population grows and urbanisation trends intensify, the dichotomy between city and nature is reinforced. As a result, sustainable urbanism concerns accompany research in urban planning and architecture. Current research in sustainable urban planning emphasises the importance of plants and planted spaces and favours implementing and conserving urban greenery (Ong, 2002). In that respect, traditional approaches to establishing greenery (i.e., public parks, backyard gardening, and street landscaping) are held to be the standard. Less typical approaches that focus on the positive impact of vegetation on architecture are referred to as 'Biophilic Architecture' or 'Biophilic Design' (Kohler, Schmidt, & Laar, 2003) or 'building-integrated vegetation' (Grant, 2006). They use architecture to increase the amount of integration between urban buildings and plants (Ambasz, 2009). As cities become denser and environmental awareness grows, the latter approaches may play a larger role because they scale better for higher densities. One of these approaches is living walls – using vertical surfaces in the built environment as platforms for growing vegetation. Vertical surfaces are traditionally not considered real estate per se, as they have no commercial value beyond advertising. This renders any city's abundant vertical surfaces potential sites for introducing vegetation into the built environment.

1.2.2 Potential benefits of living walls

Although living walls are still an emerging technology, their integration with the built environment is gaining momentum and popularity. The main incentives currently driving this trend are related to aesthetics (Perini, 2012) and to "green" promotion rather than urban sustainability, because living walls have great visibility.

Notwithstanding, current research regarding living walls' benefits and challenges suggests that they can potentially improve buildings' thermal performance, enhance air quality, modulate runoff, and contribute to human well-being and acoustics, even as they supply platforms for urban nature and urban agriculture (Dunnett & Kingsbury, 2008). Negative impacts of living walls include the high costs of set up and maintenance, engineering challenges, high water consumption, and more. These social and environmental impacts are obviously associated with the characteristics of the living walls, so that the design of a specific living wall influences the type and amount of benefits it can generate.

The underlying premise motivating this research is that, far from being an attractive, green-washing gimmick, **living walls can actually enhance urban sustainability**.

1.3 Sustainability as a Design Problem

As a designer, my natural inclination is to develop positive change through design. Moreover, the Positive Development paradigm proposes that sustainability is not a technical problem, but a design problem (Birkeland, 2008). Other researchers stress the potential impact that design has on achieving sustainability (Davison, 2013; Ehrenfeld, 2008). Accordingly, this study's approach focuses on matters of design rather than quantitative assessment. Thus, living walls' contribution to urban sustainability was transformed into a design problem, looking for optimal designs for sustainable living walls, or more precisely:

Seeking living wall designs that maximise their environmental and social benefits.

An architect/designer/user's role is not only to decide whether to incorporate a living wall, but also to make appropriate design-related decisions regarding its morphology, aspect, dimensions, irrigation, and plant selection, among others.

The purpose of this research is to connect accumulated knowledge to design decisions and design parameters, eventually formulating a theoretical basis for designing successful living wall projects that are optimised for urban sustainability. Since the aspect of cost was out of scope for this research, optimising for urban sustainability is translated to optimising environmental and social benefits in urban areas. The designer's point of view was also an important factor in adopting the methodological approach for this research: living walls' design and performance parameters were identified, and then the relationships between these parameters were studied to generate knowledge that supports and informs the living wall design process.

1.4 Context For the Study

1.4.1 Focusing on living walls in Tel-Aviv

Although the abundance of vertical surfaces characterises all cities to some extent, the amount and type of vertical surfaces differ from one city to the next. Moreover, climate conditions significantly influence the energetic considerations related to environmental features. Social contexts may also play an important role in design decisions.

Several studies carried out in Tel-Aviv ground this research. To demonstrate the study's scalability, a thermal simulation study was also done in Brisbane, as both Tel-Aviv and Brisbane are characterised by warm climates: Tel-Aviv has a Mediterranean climate while Brisbane's is sub-tropical. Brisbane and Tel-Aviv are characterised by different cultures and languages, have different architectural styles, and generally use different building materials, but both are striving to enhance their sustainability.

In Tel-Aviv urban consolidation adheres to the principle of 'de-concentrated concentration', as this is outlined in the National Outline Plan for Construction, Development and Conservation (Assif, 2005). According to this principle, the population should be dispersed at the national level but concentrated at the city level. Yet living walls, as an urban vegetation practice for dense cities, are rarely used in Tel-Aviv and scientific research on living walls' environmental impact is very limited in Israel and throughout the Middle East. Living walls would also support the ongoing process of urban consolidation in Brisbane as part of that city's South East Queensland Regional Plan (Hincliffe, 2009).

1.4.2 Small-scale research of exterior living walls

The scale of this research is largely limited to the domestic and single-building environment, with some degree of neighbourhood context. The research does not attempt to establish city planning level principles, nor does it attempt to assess environmental impacts at the city level (e.g., urban heat island reductions using living walls). It does, however, focus on the building and the user, with some analysis and discussion pertaining to the block or neighbourhood level. The various studies comprising this research deal with small- to medium-size living walls. Its results are thus most applicable at the single wall or single building level.

Another important clarification is that this work focused on vertical vegetation growing on exterior living walls as opposed to interior walls. Interior living walls' characteristics differ in a number of important ways. Firstly, they have much less interaction with the elements and therefore exhibit reduced thermal and hydrological potential. Secondly, they usually accommodate shade-loving plants, which have different attributes from sun-loving plants (e.g., mostly non-edibles, few colourful flowers, etc.). Finally, interior living walls impact buildings' indoor air quality and therefore necessitate different plant choices than exterior living walls. (Indoor wall considerations emphasise air filtration capacity, dust particle capture, and moisture enhancement, for example.) This work focuses on exterior living walls that are expected to exhibit greater environmental and social impacts.

1.4.3 Defining design decisions

Design in this research relates to all decisions that pertain to living wall projects, including the design of a new living wall system or choosing an existing system), the choice of vegetation, irrigation and growing substrate, and the installation parameters, which include the wall's aspect, the distance from the building, the dimensions, et cetera. Such decisions can cross boundaries between various disciplinary fields of: architecture, landscape architecture, garden design and product design, to name a few. This data collection and analysis (see section 1.4.2) does not, however, directly address urban planning or town planning, as noted previously. It is largely limited to the single walls or buildings magnitude.

1.5 Research Aim, Objectives and Questions

The aim of this research is to *optimise living wall design solutions for positive social and environmental impact*. Its research objectives are to:

- generate and assess both *design* options and the potential *performance* aspects of urban exterior living walls;
- assess the *relationship* between living wall design decisions and their environmental and social performance; and
- develop a *theoretical basis* for the design of living walls for positive social and environmental impact.

The first objective, generating design options and assessing the available designs and performance aspects of living walls, extends our understanding of both the variety of living wall designs and the potential influence living walls can have on social and environmental aspects. This is expected to not only identify the potential environmental and social benefits, but also to assess their relevance and importance, a knowledge base that then enables us to address the second objective.

The second objective, assessing the relationship between living walls' design decisions and their environmental and social performance helps identify patterns in that relationship. It generates descriptions of the influence specific design decisions have on specific performance aspects, which forms a major part of this research.

When these two objectives are addressed, a third objective then involves the development of the generated knowledge into a theoretical basis, to support designers in creating living walls that maximise environmental and social benefits.

The research questions addressed in this work were formulated around patterns in the relationships between the design of living walls and their performative aspects. The specific facets of this relationship, and the corresponding research questions, were determined after particular knowledge gaps were identified and prioritised as part of the literature review (see section 2.4).

The research questions were:

1) In what ways do different living wall systems relate to edible living wall performance?
2) In what ways do living wall context and design parameter values relate to their performance, from the users' point of view?
3) In what ways do living wall design parameter values relate to buildings' energy consumption?

1.6 Thesis Outline

This chapter introduced this research's aim to optimise the design of living walls for positive environmental and social impact. Chapter 2 reviews the existing literature related both to living walls in general and to their association with urban sustainability, highlighting knowledge gaps that this study then targeted. The principal knowledge gaps identified were related to specific aspects of the relationship between living walls' design and their performance, such as the influence of substrate volume on the living wall's ability to produce food. The third chapter outlines the design-oriented methodology developed to carry out the parametric relationship research, as well as the influence that a post-positivist theoretical lens, systems theory, positive development, and parametric thinking had upon that research. Three distinct methods used to collect and analyse data are detailed in Chapter 4, and the next three chapters convey the results of those studies: domestic edible living wall case study, living wall user survey, and building thermal simulation of living walls. The results are synthesised in Chapter 8, and the findings are discussed and compared to existing knowledge in Chapter 9, which includes an emerging parametric model of living walls. The final chapter outlines the findings' implications as well as their limitations. It suggests that the living wall design process should be guided by their functions, and makes recommendations for both practical implementation in design work and for future research.

2 Living Walls’ Design Decisions and Performance Assessment

In order to explore the design of living walls and their contribution to urban sustainability or, more specifically, their environmental and social performance, it is helpful to first review existing knowledge regarding living wall design decisions and their potential environmental and social repercussions. This chapter begins by defining living walls and then maps their related design decisions (2.1). The next section (2.2) reviews the existing academic literature on living walls' potential environmental and social performance according to the following aspects: thermal performance, air quality, human wellbeing, urban agriculture, biodiversity, hydrology, noise reduction, and facade protection.

The assessment of living walls’ sustainability is a fundamental step in the process of supporting the design of living walls to promote urban sustainability. Accordingly, section 2.3 reviews sustainability assessment approaches and tools in the specific context of the built environment, which serves as the foundation to forming a performance assessment approach suitable for this research. Finally, section 2.4 summarises the literature review, including any knowledge gaps and implications.

2.1 Design Decisions for Living Walls

The term *living walls* describes “vegetation that grows directly onto a building’s facade” or “vegetation that is grown on a separate structural system that is adjacent to the wall and sometimes attached to it” (Loh & Stav, 2008, p. 6). In this work, the definition of living walls is extended to include vertical vegetation growing on or adjacent to any vertical surface, not just building facades. Thus, a living wall is defined as **vegetation growing on or adjacent to a vertical surface**. Other similar terms are *green walls*, *green facades*, *vegetated facades*, *vertical vegetation*, and *bio walls*.

The terms *interior living walls* and *exterior living wall*s are both commonly used, depending on whether they are located on the inside or the outside of a building. This research focuses on exterior living walls and how they may impact the urban environment. Living walls can be designed in various ways, and they differ in many facets that are reviewed in the next sections.

2.1.1 Choice of Living Wall Technology

The primary classification of vertical vegetation, as suggested by a few authors (Dunnett & Kingsbury, 2008; Kohler, 2006; Wood, Bahrami, & Safarik, 2014), differentiates between green facades (also called *facade greening [*Dunnett & Kingsbury, 2008] or facade-supported green walls [Wood et al., 2014]) and living walls. Green facades refer to vines and climbers that grow from the ground or from large containers at various locations around the building. The climbers are supported either by the wall itself (a *direct greening system*), by a supporting trellis/mesh (an *indirect greening system*; Ottele, Perini, Fraaij, Haas, & Raiteri, 2011), or a double-skin green facade (Hunter et al., 2014). Wood et al. (2014) divided green facades that are not supported directly by the wall into the categories of *metal mesh green walls*, *cable supported green walls*, and *rigid green walls*, according to their particular support systems. In this work, *living walls* will be used as a more general term that includes green facades. Other living walls consist of plants that grow from a vertical layer of growing substrate, and these are usually classified as *vegetated mats* and *modular living walls* (Kontoleon & Eumorfopoulou, 2010; Wood et al., 2014). A visual presentation of these three main types is presented in Figure 2.1.

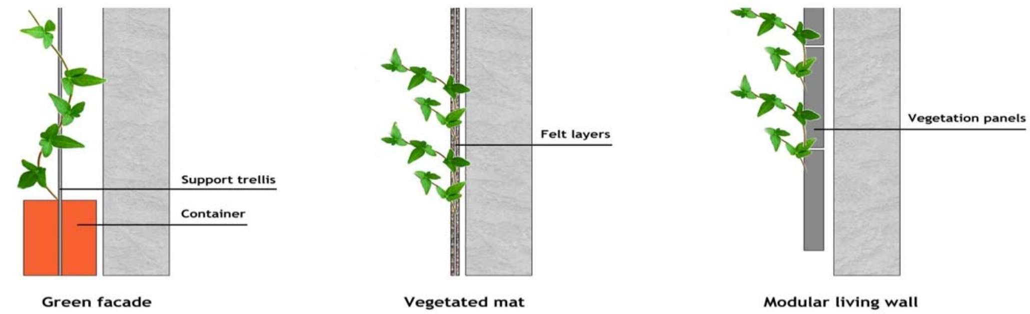

Figure 2.1. Three main types of living walls

A third type, the *hanging pocket living wall* (Wood et al., 2014) can be regarded as a sub-class of modular living walls. The vegetated mat living walls, also called *felt system* (Loh & Stav, 2008) or *living wall system based on felt layers* (Ottele et al., 2011), are based on hydroponically grown plants, typically planted in layers of synthetic felt. Modular living walls, also called *panel systems* (Loh & Stav, 2008), or *living wall systems based on planter boxes* (Ottele et al., 2011), grow from panels or pockets or planter boxes, usually filled with a loose growing substrate (e.g., potting mix or perlite). These modules are typically one of the following:

- flexible pockets made of synthetic fabric;
- rigid pockets or planters made of plastic/wood;
- rigid plastic/metal containers with slanted cells filled with substrate; or
- wire cages holding a substrate-filled fabric.

Other vertical vegetation types include *espalier*—trees trained to grow like vines (Edmunds, 1986), *wall planting*—large vegetation planted in large containers on balconies or terraces (Dunnett & Kingsbury, 2008), and walls covered with moss cladding (Wood et al., 2014). These types are not specifically addressed in this research. Figure 2.2 depicts this living wall typology.

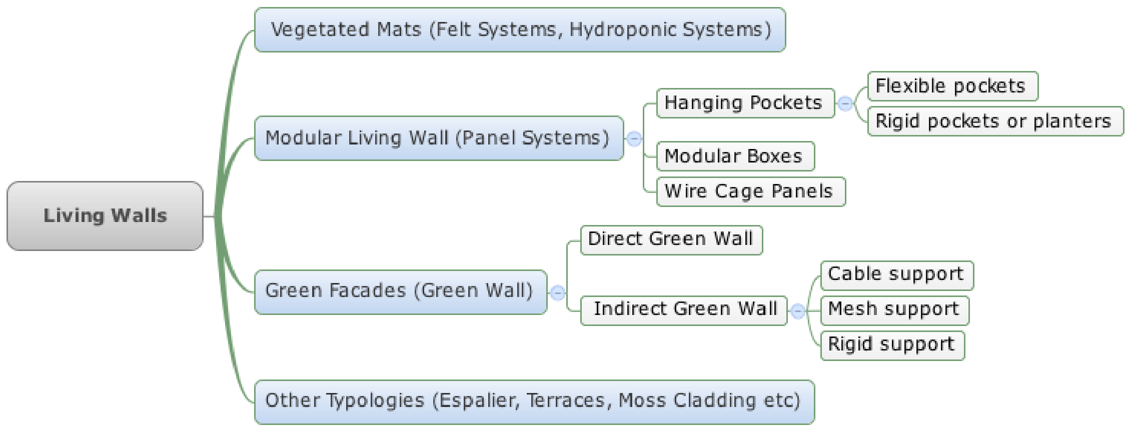

Figure 2.2. Map of living wall typology reflected in the literature

Growing plants vertically demands a growing substrate, “preferably inert and non-biodegradable” (Dunnett & Kingsbury, 2008, p. 241). Indeed, other technological classifications of living walls attach more significance to the growing substrate, therefore classifying living walls into hydroponic systems (noted in this work as *vegetated mats*) and *modular boxes*. According to Weinmaster (2009), the substrate of living walls based on modular boxes can include rockwool, coco-coir, peat, or potting soil. However the variety of substrates used in living wall projects is much more extensive. In fact, living walls can be classified into the following divisions according to the growing substrates that they utilise:

- mat substrates used by vegetated mats—usually nonwoven textile made of polyester, polyurethane, or polyamide–polypropylene (Franco, Fernández-Cañero, Pérez-Urrestarazu, & Valera, 2012);
- solid substrates—for example, rockwool (Jørgensen, Dresbøll, & Thorup-Kristensen, 2014) and fytocell (Welleman, 2004); and
- loose substrates—for example, potting mix or artificial substrate.

To summarise the research literature, then, the major design decision for living walls is related to the choice of technology used: the form of the living wall system, the support for the vegetation, the position and structure of the growing substrate, the materials and dimensions of the growing substrate, and the irrigation system (i.e., hydroponic or not).

2.1.2 Additional Design Decisions for Living Walls

Green roofs are classified in the literature into two main types according to whether the maintenance requirements are intensive or extensive. Intensive green roofs utilise deep substrate layers of more than 15 cm, include irrigation, and require more maintenance. They are often accessible and intended to be used as a conventional garden (Dunnett & Kingsbury, 2008; Scholz–Barth, 2001). Extensive green roofs use substrate layers of less than 15 cm, no irrigation, require minimal maintenance, and are lightweight. They can be implemented on roofs that are pitched up to 30 degrees (Dunnett & Kingsbury, 2008). Less commonly used terms are *simple-intensive* and *semi-intensive green roofs*. Interestingly, existing research assumes that only green facades can be considered extensive living walls and that all other types of living walls are classified as intensive (Perez, Rincon, Vila, Gonzalez, & Cabeza, 2011). However, living walls' maintenance levels range along a continuum from extensive to intensive, and classifying them according to several levels of maintenance can therefore be useful in this discourse. Such classification could be based upon the living wall's frequency or difficulty of maintenance, watering frequency, fertilisation methods, and plant selection.

A significant influence on living walls' maintenance requirements is the choice of plants. Plant selection not only ensures that the plants can survive in the specific conditions offered by the living wall, the selection also influences the wall's maintenance level and appearance (Wood et al., 2014). Therefore, this research considers maintenance levels, watering and feeding schedule, and plant selection as additional design decisions related to living walls.

2.2 The Performance of Living Walls—Environmental and Social Benefits

The list of potential benefits attributed to living walls is long and includes reducing building energy consumption, air filtration, aesthetically improving the urban landscape, increasing property values, and extending wall surface life. Other benefits attributed to green roofs that may be relevant to living walls as well are related to stormwater mitigation, runoff quality improvement, food production, fire prevention, and increased biodiversity.

Research specific to living wall benefits is limited in comparison to green roof studies. Numerous Japanese organisations and firms have been researching, building, testing, and monitoring various modular living wall systems for over 15 years. This comprehensive body of research includes aspects of thermal performance, acoustics, moisture retention, and plant performance, but the results are only available in Japanese script (Sharp, 2006). Over the last decade, however, the amount of academic research related to living wall benefits has significantly increased—no less than 22 peer-reviewed papers studying living walls were published from 2005 through 2014 (Safikhani, Abdullah, Ossen, & Baharvand, 2014), in addition to several living wall review papers.

Living wall challenges are associated with manufacturing, installation and maintenance costs, engineering complications, water consumption, building surface damage, the danger posed by venomous snakes and spiders having easier access to windows (Dunnett & Kingsbury, 2008), as well as greater vulnerability to termites. Several manuscripts, some of them academic studies and some related to the commercial application of living walls, focus on living walls' set up and maintenance costs (Ottele et al., 2011; Perini & Rosasco, 2013; Pulselli, Pulselli, Mazzali, Peron, & Bastianoni, 2014; Wood et al., 2014). The most prevalent arguments are that the technical considerations related to living walls are complicated and that the cost of the technology is too high to justify the benefits. Because this work focused upon optimising living wall design rather than aspects related to their economic feasibility, the technical and economic challenges of living walls do not fall within the scope of the literature review. Research results related to living walls' potential benefits are detailed in the next sections.

2.2.1 Thermal Benefits of Living Walls

Living walls can cool buildings in warm climates by shading them, adding to the amount of exterior wall insulation, evaporating moisture from the growing substrate, and transpiring moisture from leaf surfaces. The thermal impact of eight different living wall systems in a Singapore study found that vertical vegetation reduced the surface temperature of building facades in a tropical climate by up to 11.58 °C (Wong, Tan, Chen, et al., 2010). In subtropical Hong Kong, vegetated cladding was found to reduce interior temperatures by up to 14.5 °C by delaying the transfer of solar heat (Cheng, Cheung, & Chu, 2010). Consistent temperature reductions were also recorded in a study of green facades and living walls in Malaysia (Jaafar, Said, Reba, & Rasidi, 2013), and a model for estimating vertical vegetation systems' heat flux transmission that was developed and tested in Hong Kong (Jim & He, 2011) showed that south-facing living walls absorb large amounts of heat flux due to evapotranspiration.

Green facades in a Mediterranean climate, on the other hand, were shown to create a microclimate between the wall and the vegetation, characterised by slightly lower temperatures and higher humidity—(up to 7% more) (Perez et al., 2011). Another Mediterranean climate study measured the difference in temperatures between a wall covered with green facade and a bare wall (Eumorfopoulou & Kontoleon, 2009). The results show that the cooling effect of the internal surface of the wall in summer averages 0.9 °C. A similar study in a temperate Mediterranean climate indicated that living walls reduce the external wall surface temperatures by up to 20 °C on sunny summer days (Mazzali, Peron, Romagnoni, Pulselli, & Bastianoni, 2013).

Probably the first simulation-based study for vertical vegetation reported was a model of a double-skin facade with plants that used measurements of real plants in a test facility and incorporated these properties into the model (Stec, van Paassen, & Maziarz, 2005). The shading effect of the vegetation resulted in as much as 19% savings in cooling energy consumption.

Only a few studies have investigated specific parameters of vertical vegetation and their impact on cooling: Both a simulation of energy transfer and an urban heat island (UHI) reduction of vertical vegetation in a tropical climate found that full coverage of a building with vertical vegetation can significantly reduce the building envelope's thermal transfer value (Wong et al., 2009) and that the efficiency of the related thermal transfer reduction depends heavily on the vegetation's Leaf Area Index (LAI).

Another study investigated the influence of orientation and the percentage of living wall coverage in a Mediterranean climate (Kontoleon & Eumorfopoulou, 2010), concluding that a proper incorporation of a vegetation-covered wall in a building envelope improved the building's energy efficiency and that this effect was more pronounces on east- and west-facing walls. Other studies that compared different living wall systems concluded that green facades cool less effectively than living walls with a substrate layer (Perini, Ottelé, Haas, & Raiteri, 2011; Wong, Tan, Chen, et al., 2010).

On a larger scale, research related to green roofs and other forms of urban vegetation showed that vegetation can be a useful strategy to mitigate the UHI (Bass & Baskaran, 2003; Köhler, Schmidt, & Laar, 2003; Oliveira, Andrade, & Vaz, 2011; Peck, 2001). Nevertheless, no specific studies investigated living walls' potential role as a UHI mitigation tool (Safikhani et al., 2014) at either the neighbourhood or city scale.

To summarise, then, it is recognised that living walls decrease buildings' energy consumption significantly, and may well decrease the UHI at the city scale. However, few studies relate how living walls' design characteristics (i.e., variables of wall aspect, extent of wall coverage, plant species selection, growing substrate material and geometry, water availability, etc.) can be modified to influence the extent of thermal impacts.

2.2.2 Improving Air Quality using Living Walls

NASA's studies of self-contained ecological systems demonstrated vegetation's ability to filter and absorb atmospheric pollutants (Grant, 2006). Vegetation can assimilate very small particles and air-polluting gases into the leaves via the stomata (Fowler, 2002) and can deposit particulate matter (PM) mainly on the outside layers of leaves, trunks, and twigs. Particular plant species (e.g., those with hair and wax cover) contribute to better PM accumulation (Saebo et al., 2012). The Forest Service of the United States Department of Agriculture supplied the Urban Forest Effects (UFORE) model to determine the reduction levels of atmospheric pollutants (O_3, SO_2, NO_2, CO, PM_{10}) due to distribution of urban vegetation habitats, and to estimate the monetary value of those reductions (Nowak and Crane, 2000).

Specific knowledge pertaining to living walls' ability to improve indoor air quality (i.e., biofilteration) was generated by a company (Air Quality Solutions) which built several living wall projects and claimed that they can sequester CO_2 and remove significant amounts of VOCs (volatile organic compounds), thus improving indoor air quality (Darlington, Dat, & Dixon, 2001). Biofilteration is considered a primary benefit of the interior living wall in the Robertson Building in Toronto, Canada, for example, and fans were installed behind the wall to maintain airflow through the plants (Gonchar, 2007).

Research specific to living walls was conducted in Berlin, including a 10-year project that reported significant indoor air quality improvement in an outside-facing green facade (Köhler et al., 1993). Another study of a green facade subject to the pollution of an inner-city street in Dusseldorf reported results derived from analysing heavy metal elements in and on leaves—Up to 4% of inner-city dust was trapped by green facade plants(Bruse, Thönnessen, & Radtke, 1999). More recent studies that concentrated on fine dust particles concluded that vertical vegetation forms sinks that trap "significant quantities of health-damaging particles from the atmosphere" (Ottele, van Bohemen, & Fraaij, 2010; Stemberg, 2010), specifically PM_{10} particles. Another study, focusing on street-level air quality demonstrated that living walls can reduce levels of PM_{10} by up to 60% and NO_2 by as much as 40% (Pugh, MacKenzie, Whyatt, & Hewitt, 2012). These values indicate significant potential for living walls to tackle urban air pollution.

2.2.3 Contribution to Human Wellbeing

Greenery and nature's therapeutic effects were analysed as early as the 1980s. One of the documented effects was shorter recovery times for hospitalised patients (Ulrich, 1984) and generally improved psychological and psycho-physiological effects such as lowered blood pressure and increased positive feelings (Ulrich, 1986). More recent studies suggest that people generally prefer a view of natural settings rather than congested or cluttered built environments (Farley & Veitch, 2001). It is also suggested that a view of gardens and green plants restores calm and reduces stress (Velarde, Fry, & Tveit, 2007).

In the workplace contexts, accessibility to nature improves worker satisfaction, enthusiasm, and concentration and reduces frustration (Banting et al., 2005; Kaplan, 1993). The green facade of Melbourne City Council's CH2 building was considered by 75% of its occupants to have either a positive or a neutral effect on productivity (Paevere, Brown, Leaman, Luther, & Adams, 2008). Living walls in office buildings "reconnect workers to the biophysical benefits of vegetation, and increase worker productivity and reduce the number of sick days" (Hopkins & Goodwin, 2011, p. 40).

Results of urban research projects support the theory that people's exposure to natural elements "increases their ability to focus, cope with stress, generate creative ideas, reduce volatility and promote the perception of self as part of a meaningful greater whole" (Banting et al., 2005, p. 24). Several studies showed that landscaping positively impacted rental rates of both commercial and residential properties. The Council of Tree and Landscape Appraisers of Illinois estimated an increase of 20% in rental rates resulting from aesthetically pleasing landscaping (Laverne & Winson-Geideman, 2003).

A comprehensive review of research studying potential links between green infrastructure and ecosystem health on one hand, and human health and wellbeing on the other, claimed that green space contributes to human health via increased longevity, better self-reported health, improved attention-demanding cognitive performance, increased positive emotions, increased recovery from stress, reduced mental fatigue, regulation of feelings, and sense of community (Tzoulas et al., 2007).

The only related perceptual study directly related to living walls showed that houses with green roofs and living walls (and green facades specifically) are generally preferred over houses without greenery. The houses with green roofs and/or living walls were perceived as more beautiful and restorative (White & Gatersleben, 2011). In summary, living walls can potentially offer a multitude of effects that are beneficial to human health and wellbeing, since green views and the presence of greenery are known to supply these benefits. However, very little work has been done to directly establish these benefits for living walls specifically.

2.2.4 Living Walls for Urban Agriculture

Living walls as urban agriculture offer another obvious benefit. Where land is scarce, their vertical aspect can be utilised to grow a variety of crops. A simple definition of urban agriculture refers to a process of "agriculture production that takes place within the urban and peri-urban region" (Holland Barrs, 2002, p. 13). In this context, only horticulture is discussed and therefore the process of agriculture production includes growing food (i.e., vegetables, fruits, grains, and mushrooms), medicinal plants, herbs, and ornamental plants. Knowledge generated thus far related to urban agriculture's effect on the environment indicates that "further development of urban agriculture can substantially help to reduce urban ecological footprints" (Deelstra & Biggelaar, 2003, p. 174).

One of the key concepts used to measure agriculture's environmental costs is *food miles* (the distance that food travels to get from where it is produced to where it is consumed), although other measures, including the energy used for production and the type of transport, should be taken into account when assessing the sustainability of urban agriculture. Overall, urban agriculture is referred to as a *cleanser* that reduces flows of energy, water, nutrients, materials, and transport from urban hinterlands to the city (Stigter, 2010). Developed nations have recently begun to consider the benefits of urban agriculture and the potential contributions it can offer to sustainability, as well as the implications of incorporating urban agriculture into urban planning and land-use policies (Howe, 2003). Some of the social and environmental benefits urban agriculture bestows are enhanced food security; improved food quality; recreational opportunities; strengthening community values; improved urban management of soils, water, and waste; and reducing food miles (Hynes, 1996; Mougeot, 2010; Ostry, Rose, Enns, & Miro, 2010; Tixier, de Bon, & Holmer, 2006). Urban farming, together with community gardens, is believed to have the potential to centre local community life (Wood et al., 2014).

Existing literature discusses green roofs' food production benefits (Kortright, 2001; Whittinghill & Rowe, 2012) and features examples of existing green roofs being used for urban agriculture (e.g., the roof garden at the Fairmont Hotel in Vancouver, Canada; (Dunnett & Kingsbury, 2008); Earth Pledge's green roof in New York City (Cheney, 2002), and more. Mandel's 2013 book, *Eat Up: The Inside Scoop on Rooftop Agriculture,* noted that "fostering relationships with rooftop farmers is essential in strengthening the local food system" (Mandel, 2013, p. 16). Despite the multitude of benefits derived from urban agriculture and the growing tendency to use green roofs for agricultural purposes, only anecdotal references to food producing living wall projects exist. That said, some manufacturers are developing, installing, and testing prototype living wall systems designed to grow food vertically (Wood et al., 2014).

In summary, a living wall designed for urban agriculture may provide a multitude of environmental and social benefits such as improving access to fresh food, reducing the environmental impacts associated with the traditional food system, and strengthening community interaction. However, no academic work thus far specifically addresses these benefits of food producing living walls.

2.2.5 Living Walls for Increased Biodiversity

Some related studies focus on green roofs in the urban environment and their ability to provide habitat for a wide range of plant, bird, and insect species (Brenneisen, 2006; Dunnett, Nagase, & Hallam, 2008; Lundholm, 2006; Madre, Vergnes, Machon, & Clergeau, 2013). Recent studies suggest that green roofs and living walls may serve as reconciliation ecology, by which "the anthropogenic environment may be modified to encourage non-human use and biodiversity preservation without compromising societal utilisation" (Francis & Lorimer, 2011, p. 1429).

In 2011, Francis et al reviewed 19 botanical surveys of wall flora, that researched the spontaneous ecology developing on building walls (Francis, 2011). Recent studies, however, analyse walls as a potential habitat and as a tool for enhancing urban biodiversity. It is argued that applying ecological engineering techniques to living wall systems may increase their potential to function as habitat and that they may also potentially be used to connect urban ecosystems with green roofs (Francis, 2011). Plant selection is one of the most important design decisions involved in creating a living wall targeted towards enhancing urban ecology. The first factor is choosing plants that can survive and spread on the living wall substrate, mainly a shallow layer of substrate (Mårtensson, Wuolo, Fransson, & Emilsson, 2014). Another factor is using a diversity of plant species to better utilise existing resources (Lundholm, 2006). A recent study in the UK (Chiquet, Dover, & Mitchell, 2012) argues that green facades may be an effective way to provide a range of resources for birds—particularly blackbirds, song thrushes, and house sparrows (van Bohemen, Ottelé, & Fraaij, 2008)—in urban areas without incurring expensive additional land take. Earlier research with green facades in Berlin found mainly house sparrows, blackbirds, and greenfinches within the vegetation (Kohler, 1993).

To summarise existing research, green roof ecologies and spontaneous wall ecologies highlight the potential of living walls to enhance urban ecology and biodiversity by supplying habitat for flora and fauna. Living walls may also be designated as a habitat that connects isolated pockets of green roofs to ground level habitats.

2.2.6 Living walls' Hydrological Benefits

Green roof research demonstrates that they delay peak stormwater runoff and retain a large amount (19%–98%) of the runoff (DeNardo, Jarrett, Manbeck, Beattie, & Berghage, 2005). The depth of the green roof substrate layer is a major factor affecting this stormwater-runoff relationship (Mentens, Raes, & Hermy, 2006). A study of hydrological modelling demonstrated that widespread implementation of urban green roofs can "replicate the interception and evapotranspiration aspects of the water cycle found in less disturbed environments" (Carter & Jackson, 2007, p. 84). It is known that plant roots and the microorganisms surrounding them help to purify water in, for example, constructed wetlands (Brix, 1994), but how this filtering process is influenced by the vertical orientation of living walls and the various artificial substrate types is not yet known. Ostendorf et al.'s (2011) study of stormwater runoff moderation by green retaining walls demonstrated their potential to substantially reduce runoff. It also emphasised the importance of plant selection and, even more importantly, of the growing substrate.

Research specifically targeting living walls' capacity to filter and regulate stormwater was not found, but a few existing living wall projects—for example, the interior living wall in Bertschi School in Seattle (GSky, 2015) and the green facade system in Melbourne's CH2 building (Rayner, Rannor, & Williams, 2010)—do use grey water for irrigation. Doing so allows the living wall to play "a positive and active role in sensitive urban water management." (Loh & Stav, 2008, p. 7).

In summary, the impact of living walls on urban hydrology is expected to differ from that of green roofs, owing to the vertical orientation of the substrate layer, but research regarding living walls' ability to modulate stormwater and improve runoff quality has not yet been done. Although it is assumed that living walls do supply similar hydrological benefits (Loh & Stav, 2008), the magnitude of those benefits is not yet known.

2.2.7 Noise Reduction by Living Walls

The acoustic properties of living vegetation and substrate materials allow them to serve as a sound-absorbing layer (Shiah & Kim, 2011). A Singapore study of different living wall systems (Wong, Tan, Tan, Chiang, & Wong, 2010) demonstrated that, although the sound absorption coefficient increases with greater vegetation cover, the substrate of the living wall systems is the major factor in their acoustic properties. The substrate performs well in low frequency absorbance, while the vegetation better absorbs higher noise frequencies. It can therefore be assumed with some confidence that a thicker layer of substrate improves living walls' noise reduction benefit. Other than this, there is no specific research related to how living walls' types and design parameters influence acoustic behaviour.

2.2.8 Protection of Building Facades

Living wall systems can help protect a buildings' facades and extend their life, sheltering them from heavy rain and hail and minimising damage from UV radiation (Ottele et al., 2011). A green facade was found to block around 80% of solar radiation from reaching the surface of the wall (Rath & Kiebl, 1989). Ultraviolet light damages the mechanical properties of coatings, paints, and claddings. Since living walls block UV radiation and protect walls from physical damage, they affect the building envelope's life span and maintenance costs positively (Wood et al., 2014). Given we know that green roofs extend the life of a roof by a factor of between two and four (Porsche & Köhler, 2003), it can be assumed that living walls can prolong building wall membranes in a similar way. This aspect was addressed in a green roof Life Cycle Analysis (LCA), where the green roof's savings in building maintenance due to the roof membrane's longer life span was evaluated (Saiz, Kennedy, Bass, & Pressnail, 2006). It was found that this aspect was relatively minor in comparison to the green roof's expected building-cooling energy savings. However, specific research regarding living walls' ability to protect building envelopes have yet to be conducted.

2.2.9 Summary of Living Wall Benefits

Although the social and environmental benefits of living walls are expected to be plentiful, knowledge about these is concentrated in only a few areas. Information regarding the thermal benefits of living walls is relatively abundant and focused at the building level, as opposed to UHI mitigation at the city level. There is also a large body of knowledge related to the ability of living walls to improve air quality (mainly indoors, but also outdoors to a limited extent). Knowledge related to other aspects of living wall benefits is relatively limited, and it is largely based on research associated with green roofs and other types of vegetation.

Living walls' contribution to human wellbeing, including psychological and health benefits, is expected to be similar to that related to other green spaces in the city. However, it is unclear whether the vertical configuration of living walls can augment these benefits. Knowledge pertaining to the usage of living walls for urban agriculture is largely speculative, as this practice is nearly non-existent, and the vertical orientation of living walls may impact usability and productivity. Nevertheless, assuming living walls can be used for urban agriculture, the related benefits are expected to be similar to other applications of urban agriculture.

The contribution living walls make to urban ecology and biodiversity is expected to be comparable to that of green roofs, since they add to the number of much-needed green spaces in the city. However, the technical characteristics of living walls might well alter their capacity to restore urban habitats. On the other hand, living walls can potentially cover large areas of a congested city (potentially even more than green roofs) and can create ecologically important bridges between green roofs and ground-level parks and brownfields. We know very little about their hydrology effects, but it is assumed that living walls can help filter stormwater runoff and modulate peak runoff, thus forming part of water-sensitive urban design strategies. In terms of noise reduction and the protection of building facades, although the amount of experimental data specific to living walls is not large, it is not unreasonable to expect that existing knowledge related to green roofs can be applied to living walls.

2.3 Performance Assessment of Living Walls

The review of performance assessment in the context of this research concentrates on environmental and social benefits, features that are usually included in sustainability assessments. Its aim is to understand the various sustainability assessment approaches and methods that may apply to living walls. Due to the abundant literature describing sustainability assessment practice and theory in various fields, this review's objective is limited to briefly assessing the various approaches and methods' relevance to assessing environmental and social benefits. This section first describes the broad *sustainability assessment* term and then focuses upon the specifics of sustainability assessment for living walls in the built environment.

2.3.1 Sustainability Assessment

The term *sustainability* is used in many fields and contexts and has many different definitions. Probably the most widely agreed upon definition of sustainable development is that offered by the United Nation's Brundtland Commission: Development that "meets the needs of the present without compromising the ability of future generations to meet their own needs"

(Brundtland et al., 1987, p. 24). One of the visions emerging from that basic definition conceives of sustainable development as a process that promotes both human and ecosystem endurance and wellbeing. In other words, sustainability is based on the "balance between the ever changing types and quantities of environmental life support used by society, and the long-run ability of natural ecosystems to provide life support" (Kaufmann & Cleveland, 1995, p. 1). This approach emphasises both anthropo-centric and eco-centric attitudes and defines sustainability as an inherently interdisciplinary concept.

Another widely accepted concept related to sustainability is the *triple bottom line* (Elkington, 1994). This concept divides sustainability goals into three pillars, thus adding a third 'P' (for profit) to the planet (environmental) and people (social) attributes. Debates related to the architectural metaphor of pillars supporting sustainability have been discussing whether there should be two intersecting pillars (ecological and human as reflected by the Brundtland Commission definition), three (social, ecological and economic—the triple bottom line), five (ecological, economic, social, political, and cultural), or more (Gibson, Hassan, & Tansey, 2013). However, there is consensus that, at a minimum, the anthropo-centric and eco-centric aspects of sustainability should be included, thus the present work focuses on those facets. Although other factors, especially cost issues, are often included when discussing sustainability, this works' scope integrated environmental and social aspects only.

In addition to defining a widely accepted, three-pillar model of sustainability, triple bottom line is predicated on paying attention to comprehensive outcomes, also known as *full cost accounting* (Gray & Bebbington, 2001). In the scope of this work, full cost accounting can be translated to a comprehensive approach to assessing sustainability without neglecting any social or environmental impact living walls may generate. This brief overview of sustainability definitions leads to the next relevant topic—sustainability assessment or measurement.

Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardised method of tracking and reporting the environmental impacts of a product or process throughout its full life cycle, from raw material acquisition through to production, use, and disposal (Simonen, 2014). The term *product* in a built environment context can be applied to a building or part of a building. The LCA process typically includes creating a Life Cycle Inventory (LCI) that helps to generate a Life Cycle Impact Assessment (LCIA). The LCA's impact categories include those related to resource use, ecological impacts, and effects on human health. A standardised recommendation list for the impact categories is detailed below, although most LCAs seldom include the entire list due to lack of data (Doherty, Rydberg, Ingemarson, Nilsson, & Eriksson, 2002):

- Resource use: Energy (renewable and non-renewable), materials (renewable and non-renewable), water and land (including wetlands).

- Human health: Toxicological and non-toxicological impacts, and effects on work environments.

- Ecological impacts: Global warming, depletion of stratospheric ozone, acidification, eutrophication (and oxygen demand), photo-oxidant formation, eco-toxicological impacts, and habitat alteration and impacts on biological diversity.

The result of an LCA is a list of scores for each of the impact categories. Weighing the relative costs and benefits of two projects or alternatives therefore requires comparing the various categories and applying some form of weighting mechanism.

Life cycle impact assessment (LCIA) methods aim to connect each life cycle inventory (LCI) result (e.g., specific emissions) to the corresponding environmental impacts (De Haes & Van Rooijen, 2005). The impact categories (also referred to as midpoint categories) are then grouped and correlated to create damage categories. An example of an LCIA framework is illustrated in Figure 2.3.

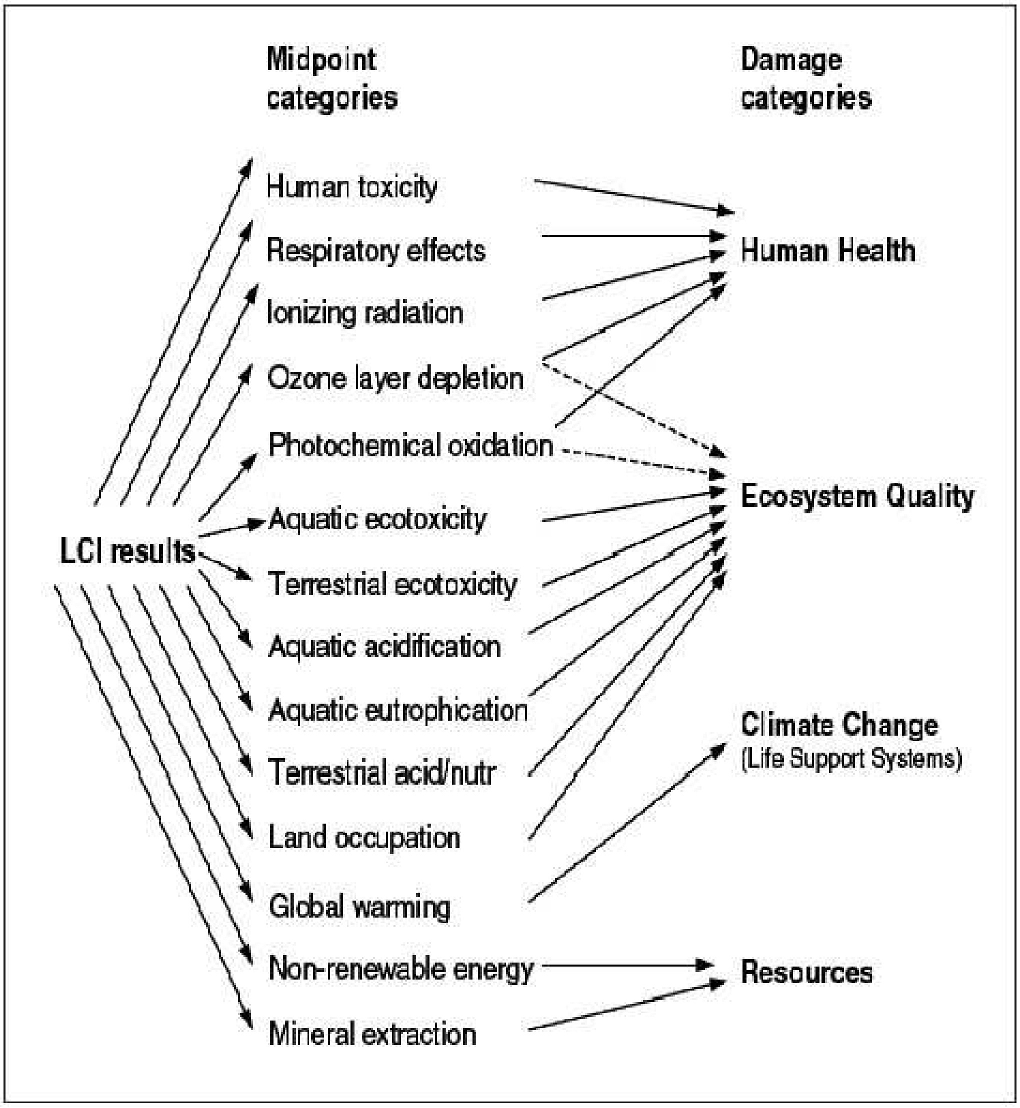

Figure 2.3. IMPACT2002+ LCIA framework (Jolliet et al., 2003)

Cost Benefit Analysis

Cost Benefit Analysis (CBA) is an economic analysis method that evaluates the costs and benefits of two or more alternatives (Hanley & Spash, 1993). In the context of sustainability, it is usually used to measure the economic aspects of natural resource use and environmental impacts, which are valued according to how much they are worth from a human perspective. The basis of a CBA is a series of monetary flows measured using a globally recognised currency such as USD or AUD. The benefit of performing a CBA is that the results (basically the monetary flows translated to net values) are easily understood and can be readily compared to other scenarios.

Valuing environmental costs and benefits monetarily is sometimes not performed at all, and when it is (in one of many different ways), it is probably the most difficult and controversial part of a CBA. Cost benefit analyses traditionally work well when used to evaluate human-centred environmental impacts (e.g., pollution costs are valued according to the taxes they inflict), but they tend to ignore their "non-use" or "future-use" values. Further discussion on financial evaluations of natural capital follows.

Life Cycle Costing

Life-Cycle Costing (LCC) assesses the costs of a product or a service from a life-cycle perspective and sometimes includes social and environmental costs (Finnveden & Moberg, 2005). It is similar to CBA, though it usually measures only the costs and not the benefits.

Ecological Footprint

Ecological Footprint (EF) is an index of biophysical impacts (Wackernagel & Rees, 1998). It measures the (biologically productive) land and water area required to support an entity's (e.g., a building) life and the various activities related to it, including the consumption of goods and services as well as waste assimilation. The EF concept was developed to measure the sustainability of nations and of humanity in general, but it can also be used at a smaller scale (e.g., populations, regions, and buildings). This is one of the sustainability assessment approaches that focuses on natural capital. The result of an EF assessment is a number that can be intuitively understood and compared. Existing critiques of EF discuss its inaccuracy, the lack of contamination estimations, and specifically point out that EFs frequently underestimate energy-related footprints.

Ecosystem Goods and Services

Ecosystem services and goods (sometimes referred to as *eco-services*) are used to describe the various functions of healthy ecosystems that are beneficial to humans, animals, and plants. These include pollination, water regulation, and waste treatment, to name a few. The ecosystem services assessment framework was used in the Millennium Ecosystem Assessment project to examine the environment (Hassan, Scholes, & Ash, 2005) and identify the connection between ecosystems and human wellbeing.

Costanza et al.'s (1998) study valued eco-services over the entire planet. It classified 17 ecosystem services (e.g., climate regulation, water supply, food production, etc.) that were assessed within the context of 16 separate biomes (e.g., coral reefs, wetlands, and deserts). The results supply a minimalist estimate of global eco-services' value to be almost twice the global gross national product. This may indicate that the value of eco-services cannot justifiably continue to be ignored, as they currently are in many sustainability assessment methods. Since many eco-services, such as improved microclimate and enhanced wellbeing, cannot be fully represented by numbers, quantification should be assisted by "surrogates" such as the area covered by wetlands or biomass volume (Heal, 2000).

When assessing a built environment project, eco-services are usually ignored, although every suggested development should be compared to the value of existing conditions (which typically embody a higher eco-services value than those of the suggested development). Many methods of assigning monetary value to eco-services have been suggested, including "costs avoided", "market price", "productivity", and more (Birkeland, 2008). Economic valuations of eco-services (or suitable surrogates) can be added to CBAs to complement the missing aspects of values that cannot be directly related to profits.

Beyond Zero Assessment

Partly inspired by the *cradle-to-cradle* paradigm, wherein wastes are turned into resources (McDonough & Braungart, 2010), new design and architecture strategies aim for a *net positive* built environment—as opposed to the usual *net zero* target (Renger, Birkeland, & Midmore, 2014). The object of net positive-designed projects is achieving positive performance with respect to energy, water, and carbon. *Positive development* suggests that the built environment be a net positive environment that is alive and can actively increase ecosystem services, as well as natural, social, and economic capital (Birkeland, 2008). In fact, existing sustainability assessment methods are criticised on the basis of their perceived reductionism, principally that they segregate factors such as human and environmental health that are inseparable. Analytical approaches that break down sustainability into individual components of indices and then aggregate them into one measure are also criticised for being too data intensive (Birkeland, 2008). Additionally, existing assessment methods conceptualise trade-offs between environmental impacts and other impacts (social, financial, or others), thus allowing negative impacts on the environment to be partially compensated in other ways.

Moreover, LCA and other assessment methods do not deal appropriately with non-human living organisms such as the ecological effects that emissions have on surrounding ecosystems. Neither do they include any of the measurements suggested by the Index of Biological Integrity (Doherty et al., 2002). In the context of living walls, LCA cannot account, for example, for improved air quality resulting from added vegetation or additional urban wildlife habitat.

Nevertheless, assessment tools such as LCA, LCC, CBA, and EF are being used to evaluate performance despite the fact that they are not suitable for anything beyond zero assessment; They "only measure negative or less negative impacts and have been criticized for their static and reductionist approach" (Renger et al., 2014, p. 12). The Carbon Amortisation Performance (CAP) model is one of the very few suggestions put forth to facilitate quantitative, beyond-zero assessment (Renger et al., 2014).

2.3.2 Classification of Sustainability Assessment Tools for Buildings

In a project titled *Annex 31*, the International Energy Agency (IEA) supplied a directory of tools developed for measuring the energy-related environmental impact of buildings. The existing tools are classified according to the following criteria:

1. Active Tools:
    a. Environmental LCA and LCC Tools for Buildings
    b. Energy and Ventilation Modelling software
2. Passive Tools:
    a. Environmental Assessment Frameworks and Rating Systems
    b. Environmental Guidelines and Checklists for Design and Management of Buildings
    c. Environmental Product Declarations, Catalogues, Reference Information, Certifications and Labels. (International Energy Agency, 2004)

Although focused on energy, this classification is broad enough to cover all types of sustainability assessment tools.

Foliente et al. (2007) suggested another way to categorise sustainability assessment tools, one that considers three dimensions: the scope of the tool (products/materials; components; whole building, portfolio, or region), the performance attributes (environmental, economic, and/or social), and the project's life-cycle stage. Another characteristic is that the tool can be used by different end-users (the architect/designer, engineer, building owner/manager, various authorities, etc.). In addition to these three dimensions, the users' objective should also be defined as a tool that can affect design alternatives, certification, meeting standards, and more. Foliente also notes that most tools are restricted to handling only one type of building—residential, office, retail, etc.—and that different tools will be better suited to either new, existing, or retrofitted buildings—a factor that is also related to the life-cycle stage noted above.

As mentioned before, there are also many ways to measure sustainability. While some tools measure only environmental factors, others measure social and economic factors as well. Tools can also measure direct/indirect impacts and short- or long-term implications. Another factor is whether the impacts considered are related only to the building or to both the building and the tenants. In addition, tools can be qualitative (mainly checking for the presence or absence of components) or quantitative.

Two more ways that tools can differ include the geographic scope (building/regional/global) and the inclusion or exclusion of both private and public costs and benefits. For example, even if one building is assessed, it should be decided whether the tool measures only costs/benefits to the human and natural capital related directly to it (building owners and users, the backyard, etc.) or whether its impacts on the region should also be considered.

In summary, the various classifications of sustainability assessment tools supply considerations for defining the most suitable assessment methods for living walls. This work emphasises assessment that is active, targeted for designers, at the product/building scale, measuring environmental and social aspects.

2.3.3 Living Wall Overall Assessment

Relatively little environmental or financial assessment of living walls has been carried out. In the Netherlands, a comparative Life Cycle Analysis (LCA) compared four types of living walls: direct green facade, steel-mesh-supported green facade, modular living wall, and vegetated mat living wall (Ottele et al., 2011). This LCA took into account the materials and energy savings resulting from thermal properties, although the energy saving calculations were only approximations, and the study did not account for the specific characteristics of each living wall system. The analysis concluded that the choice of system and the materials involved is critical. For example, a living wall based on climbers directly on the wall (without a trellis, so no materials are involved) is a more sustainable alternative than the wall only. Other than that, living walls based on modular panels could be another more sustainable alternative, but that depended on the specifications and the climate.

When an energy evaluation was performed on vegetated mat living walls that grew plants and grass (Pulselli et al., 2014), the assessment included all materials and work involved (e.g., watering system, support frames, transportation, etc.), and it also accounted for the energy savings from thermal benefits. The results showed that in certain conditions (i.e., Mediterranean climate, equator-oriented facade, and a massive building envelope), the installation of vegetated mat did constitute a building retrofit option that is an improvement in terms of sustainability.

Neither of these analyses included any living walls benefits beyond thermal energy savings, but both elaborated on the costs associated with materials and work, most likely because these are more readily estimated.

Green roof studies (Saiz et al., 2006) suggest that the significant environmental costs of living walls are those of material production, transportation, and maintenance. Maintaining living walls could potentially be more environmentally demanding than green roofs are, given the inherent challenges of access (similar to the difficulties of skyscraper window cleaning) and of retaining enough moisture in a vertical substrate. The scope of overall analyses of both living walls and green roofs was comprehensive with respect to material and work costs, but social benefits and many of their environmental benefits were generally not quantified.

In summary, both green roof and living wall overall assessments are lacking in terms of a comprehensive social and environmental benefits analysis. Many sustainability assessment methods and tools are tailored to the whole building or larger scale, although some can be used at the technology/component level (i.e. LCC and LCA) and as such are useful for performance assessment of living walls.

2.4 Implications and Summary

This literature review created a preliminary mapping of living walls' design and performance parameters (see Figure 2.4). A map of the existing design and performance spaces formed the basis for this inquiry into the relationship between living wall designs and their performance.

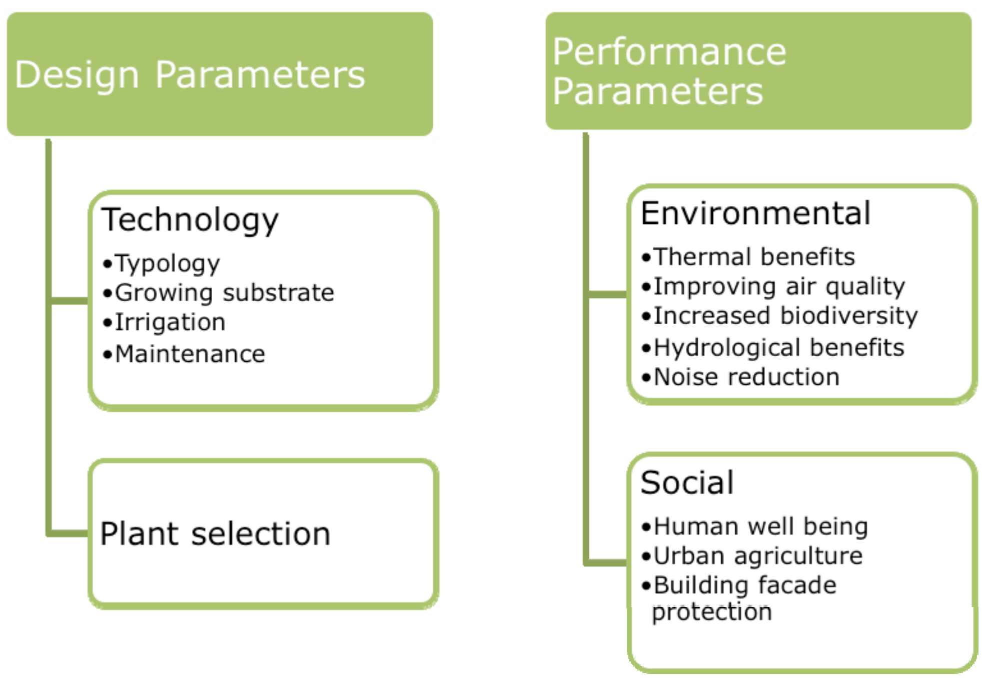

Figure 2.4. Preliminary map of design parameters and performance parameters

This literature review outlining what is known about living walls' performance indicates that academic knowledge is limited and that gaps in our understanding are abundant. For most of the benefits, partial knowledge exists or has been extrapolated from related knowledge of green roofs and other forms of urban vegetation. In order to prioritise the knowledge gaps related to the environmental and social benefits of living walls, the expected significance and design-related knowledge for each of the living walls' benefits was analysed. The priority of each knowledge gap was determined according to its expected significance and the design-related knowledge level associated with it. Table 2.1 summarises the living wall benefits that were reviewed.

The extant literature indicates that one of the most significant types of benefits are related to urban agriculture, which has been demonstrated to confer significant environmental and social benefits. However, information regarding urban agriculture using living walls is scarce. Another significant benefit of living walls is the thermal aspect. Although this is one of the more thoroughly researched performance aspects, more study is needed, especially regarding design decisions. Living walls' ability to improve human wellbeing was considered significant in the literature, but only very limited work treating that aspect had been done, and none of it was related to design decisions. These knowledge gaps were therefore highlighted in Table 2.1 and were specifically addressed in this work.

Table 2.1: Knowledge Gaps Related to the Environmental and Social Benefits of Living Walls. Shading indicates the highest priority knowledge gaps that were specifically addressed in this work.

Benefit	Design-related knowledge	Expected Significance	Priority
Urban Agriculture	None	Energy savings from decreased food miles. Improved health via fresh produce. Community related benefits (Hynes, 1996; Mougeot, 2010; Wood et al., 2014)	High
Thermal Energy	Some—related to wall aspect and to specific systems (Perini et al., 2011; Wong et al., 2010)	High energy savings in warm climates. Improved microclimate (e.g. Cheng, Cheung, & Chu, 2010)	High
Human Wellbeing	None	Stress alleviation and mental condition improvement. Positive psycho-physiological effects and increased longevity (Tzoulas et al., 2007; White & Gatersleben, 2011)	Medium
Air Quality	Some—related to plant characteristics (Saebo et al., 2012)	High impact on indoor environments and in highly polluted outdoor areas (e.g. Pugh et al., 2012)	Medium
Urban Biodiversity / Wildlife Habitat	Some—related to plant species (Grant, 2006)	Large potential to increase urban green spaces. Connecting green roof and ground level ecologies (Francis, 2011)	Medium
Hydrology	None	May be able to modulate and filter stormwater runoff (Ostendorf et al., 2011)	Low
Building Facade Longevity	None	Expected to increase life span of building facade, similar to green roofs (Ottele et al., 2011)	Low
Acoustics	Limited—related to substrate thickness (Wong et al., 2010)	Substrate layer, and vegetation to a lesser degree, can be an efficient acoustic buffer (Shiah & Kim, 2011)	Low

In terms of assessing living wall performance, a general analysis of living walls divided a range of problems in assessing living wall performance into three classes (Stav, 2008).

The first class stems from the complexity of the interaction between living walls and their environment. Site-specific variables that influence living wall performance in many ways include building orientation, layout, envelope, thermal capacity, roof-to-wall and window-to-wall ratios, temperature, humidity, wind, pollution, elevation, radiation, climate, and microclimate. Other examples of variability relate to design decisions. For example, the decision regarding whether to use tap water irrigation, grey water integration, or rainwater retention and filtration influences whether a system requires ongoing resource inputs or is self-maintaining while providing hydrological benefits. Making design choices that attract indigenous species of flora and fauna can create a living wall that actually enhances the ecology and provides a platform for local wildlife propagation rather than one that merely enlarges biomass.

The second class of problems stems from the fact that few living wall projects exist, and those that do are young. For example, when trying to estimate the extent to which a living wall may protect buildings' exterior surfaces, we find no living wall projects that are both old enough and appropriately documented.

The final class of problems is related to those living wall benefits that can only be partially quantified or, in some cases, cannot be quantified at all. Added psychological value can be measured monetarily, as has been demonstrated by a green roof CBA study (Acks, 2005), but this is a relatively narrow aspect of the effect vegetation has on people. A more holistic approach would probably attribute greater social value to living walls. Finally, such benefits as providing additional wildlife habitat and urban agriculture are not quantified at all at this time.

In addition to the inherent problems of assessing living wall performance, existing tools and practices present their own challenges. While living walls (and other types of building-integrated living systems) can potentially add beyond-zero value to a building given their ability to "retrofit cities for a range of positive human and environmental benefits" (Birkeland, 2009, p. 2), green building tools are focused on harm reduction—they measure progress from unsustainable development, not sustainability (Birkeland, 2012).

In conclusion, no tools or measurement methods have yet been found that takes into account the various benefits (particularly the many eco-services hinted at in the literature) or is capable of fully assessing net-positive living wall designs. Accordingly, using current sustainability measurement tools in this design-oriented study can help us understand whether a design decision improves a building's eco-efficiency, but they have yet to give a full picture to be used independently. Moreover, most tools were not designed for such an assessment and are difficult to adapt to the needs of this work. This aspect is further examined in Chapter 3 (Methodology).

2.4.1 Identified knowledge gaps and research questions

The principal gaps in the knowledge of living walls' environmental and social performance addressed in this work were presented and prioritised in Table 2.1. A research question was derived from each of the three top priority knowledge gaps identified (see Table 2.2).

In addition, the few existing overall assessments of living walls and several green roof assessments are incomplete and tend to focus more on costs, which are easier to quantify. A related issue is the lack of holistic sustainability assessment tools and methods, and the inherent problems in overall sustainability assessment of living walls. This situation suggests a need for an alternative, more positive approach to assessing the contributions living walls might make to urban sustainability.

Table 2.2: Identified knowledge gaps and the research questions derived from them.

Knowledge Gaps	Research Questions
The potential of living walls to support urban agriculture, and the relationship between design decisions and the performance of such edible living walls.	In what ways do different living wall systems relate to edible living wall performance?
The socially related benefits of living walls, mainly their contribution to human wellbeing that accrues from psychological benefits, educational value, and community enhancement.	In what ways do living wall context and design parameter values relate to their performance, from the users' point of view?
The relationship between living walls' design and buildings' thermal performance.	In what ways do living wall design parameter values relate to buildings' energy consumption?

3 Parametric Study for a Design Inquiry

As noted, the purpose of this research was to improve the design of living walls to maximise their social and environmental performance. The knowledge gaps identified indicate a distinct lack of research regarding living wall design and their relationship with such aspects as thermal benefits, edible living walls, and any resulting social benefits. Also identified was a methodological gap in assessing living walls' sustainability that highlighted the need for an alternative approach to living wall research.

To conceptualise the design of this research and suggest an appropriate framework to improve the design of living walls, this chapter frames this research within the realm of design research. It then discusses relevant theories related to living walls and sustainability, the theoretical worldview underlying the methodology, and the research strategy that was considered appropriate for a performance-based design problem. Finally, how the chosen methodology was operationalised is detailed.

3.1 Supporting the Design of Living Walls

Design research can be divided into two main strands: one that generates knowledge about design that is devised to better understand the design process, and another that generates knowledge for design that improves how design is practiced (Horváth, 2001). In other words, the two strands are *research* ***into*** *design* and *research* ***for*** *design* (Simonsen, Bærenholdt, Büscher, & Scheuer, 2010). A third strand, *research* ***through*** *design*, describes design and research that is inseparable, where the research is actually based on design (Frayling, 1993). But the current work belongs to the research for design strand, as it seeks to improve living wall design outcomes.

Another useful distinction is that drawn between descriptive and prescriptive research (Elen, 1995). Descriptive research attempts to understand how things are, whereas prescriptive research is goal-oriented and concerned with how things ought to be (i.e., improving the existing situation (Simon, 1996).

Regrettably, the research branch designed to improve, rather than explain and predict, is rarely emphasised in existing research methodologies (Reich, 1995). The few methodologies that incorporate ways to change the situations being studied (with the exception of Action Research) assume that the intervention can be derived from the model that was developed. These methodologies thus do not support the development of interventions (Blessing & Chakrabarti, 2009). The design research methodology (DRM) suggested by Blessing and Chakrabarti (2009) does, however, address the issue of support development, and was therefore useful for developing the methodology used in this work.

Designers are expected to supply solutions to design problems in the form of an artefact, or of a design of an artefact. Because the purpose of this research was to enhance the benefits accruing from living walls, the research is intended to support and improve the design process carried out by the living wall designer. The research problem is thus not only more general than is the design problem, it is also expected to generate a different outcome. In fact, the outcome of a research-for-design effort (support for a design process) can take any form (e.g., guidelines, checklists, procedures, etc.) and any medium (e.g., paper, software, models, workshops, etc.) (Blessing & Chakrabarti, 2009). This work seeks to develop design supports that, as recommended by Birkeland (2008), encourage creativity and innovation.

The qualities of the support developed in this work depend very much on understanding the topics of sustainability and living walls (more specifically, their environmental and social performance), but they also rely on the nature of the design problem and process. The next sections describe how systems theory illuminates the topic of living walls and how the positive development framework characterises design for sustainability before explaining the ontological and epistemological choices that frame this work's methodological lens.

3.2 Theoretical Framework

To discuss how the methodology for this research was constructed in a way that is consistent with the literature review of research regarding living walls and sustainability, it is important to incorporate three related concepts of living walls, sustainability, and design. It is also important to explicate how they inform the research's theoretical position.

3.2.1 Living walls as complex systems

This work treats living walls as complex systems, first and foremost because they involve living vegetation. Researching living walls means studying their materials and vegetation, as well as their interaction with the building, the environment, and people. Though various architectural-science or engineering research topics include a complex combination of materials and physical properties (e.g., double-skin facades), the living component is only relevant to a few of those systems.

Living systems generally convert one form of energy into another, or into information. A living system "maintains within its boundary a less probable thermodynamic energy process by interaction with its environment" (Skyttner, 2001, p. 119). Moreover, living systems are considered complex systems, as a large number of interacting entities that interrelate with each other in multiple processes and on several scales comprise them (Bellomo, 2008). The high complexity of living systems is one of the reasons computer modelling of living systems requires methods that differ substantially from those used for inert matter (Bellomo, 2008).

General living systems theory (GLS), introduced in Miller's book *Living System* (1978) integrates all types of living systems and suggests a methodological approach to study them. Other researchers suggested a conceptual framework for GLS that originated from the need to synthesise and integrate biological knowledge (Gerard, 1958; Warren, Allen, & Haefner, 1979). Living walls, however, are comprised of both inert components (construction and substrate) and living components (vegetation), so they can indeed be described as complex systems, albeit only partially living. According to general systems theory (GST), the precursor of GLS, systems of all kinds follow certain principles that can be used to study them (Skyttner, 2001). General systems theory promotes the exploration of properties, models, and the laws of systems (Von Bertalanffy, 1972). Thus, the dynamics between components of the system are at least as important as understanding the components themselves.

Furthermore, systems theory is holistic (or emergentistic), which means that it is guided by the idea that a system has emergent properties as a whole that are not necessarily explainable from the sum of their parts. "A system cannot be understood by analysis of the parts because of their complex interactions..." (Skyttner, 2005, p. 57). Thus, systems are wholes that are better understood using synthesis, which reverses the order of analytical science. Synthesis starts by identifying the system and its behaviour and then explains the particular units that comprise that system. Synthesis creates knowledge of a system's functionality and dynamics rather than its structure. Therefore, this research looks at living walls synthetically from a whole-systems point of view, focusing on the most significant dynamics in which living walls can enhance sustainability without needing to explain their physical mechanisms and underlying structures. The term *living wall dynamics* is therefore a key concept in this work.

Expressed another way, systems theory holds that it is impossible to attain total predictability owing to systems' considerable complexities. This view still affords some predictive capacity, however, as one can create a hierarchy of those system parameters that appear to have the greatest impact upon an event. Organising these parameters improves the capacity to predict. This principle was implemented in this work by initially identifying and sorting the parameters according to their significance in improving performance, and then examining living wall dynamics-the way changes in the values of each parameter influenced living wall performance.

3.2.2 Positive approach to sustainable design

The previous section noted that systems theory recommends studying a system's parameters according to their expected impact on the system's performance. A similar concept suggests that performance criteria, also termed success criteria, can be used to focus the study of the present situation and to assess the contribution of various factors such that the most relevant factors can be focused upon (Blessing & Chakrabarti, 2009). The performance criteria for living walls in this work's context are all related to environmental and social benefits. Assessing those benefits is very much related to assessing sustainability, and therefore sustainability is useful for defining performance criteria here.

As discussed in the literature review, there is an ongoing scholarly debate regarding the search for the ultimate definition and indicators of sustainability (Kaufmann and Cleveland, 1995). Because most definitions describe sustainability according to concepts from different and often dichotomous disciplines, its assessment must employ a multidisciplinary or holistic approach. A single discipline cannot fully encompass the knowledge required for all sustainability pillars. For example, if a living wall's economic impact is chosen to be an indicator of its sustainability, it will obviously require economic tools, but to quantify the economic impacts properly, information about the ability to save cooling energy, to prolong the building envelope, and to supply ecosystem services must all be incorporated.

According to the principles of positive development, sustainability assessment should assume that the ecological base or eco-services constitute the bottom line that is being measured (Birkeland, 2008). Such assessment would be positive in the sense that instead of measuring the damages, it should assume potential improvements. Positive development assessments of sustainability should thus compare the development to the existing site's baseline or to existing building conditions, seeking improvements that will enhance eco-services beyond the baseline—net zero, zero waste, or zero energy are not sufficient (Birkeland, 2008). This approach stresses the value of living systems, as they are the most likely to create additional eco-services, as opposed to simply not harming pre-existing eco-services. Birkeland also explains that existing environmental tools focus on the symptoms of the environmental problem such as carbon emissions and pollution, instead of looking at the root causes and finding solutions at that level. Positive development does not offer any present sustainability assessment methods, though recommendations are made for future methods (Drogemuller & Frazer, 2008), but it does help understand the limitations of sustainability assessment methods and their inherent shortcomings. Its focus on enhancement also highlights an optimistic pathway to higher, net-positive goals (see section 2.3.1) and suggests using future-thinking tools that help expect the unexpected (Birkeland, 2008). The conclusion then follows that sustainability assessment, especially in the context of living walls, is debatable, and that no current assessment approach is suitable. However, this research suggests that design is the key to making progress towards achieving real sustainability.

According to Birkeland, sustainability entails meeting needs and desires in new ways, which renders it a design problem (Birkeland, 2002). The conceptual role of design as the major player on the path to sustainability is one of the building blocks of positive development. As other researchers have noted, design offers a pathway to change the current unsustainable course in the search for the best way to achieve sustainability (Ehrenfeld, 2008). It is claimed that alternative directions in design can potentially widen the field of possibility and change the current unsustainable condition (Davison, 2013), an argument that supports the decision to focus on design support and empowerment in this research.

To summarise this section, then, there is currently no useful way to assess living walls' sustainability. Furthermore, real, net-positive sustainability can only be advanced by enhancing environmental and social benefits, and that can only be achieved by realizing new possibilities through innovative design. For these reasons, this research focuses on ways to enhance the sustainability of complex systems of living-walls-and-buildings-in-context.

3.2.3 Seeking an objective representation

Having noted how general systems theory and positive development provide the framework for this investigation, the role played by the researcher is now described. From an ontological and epistemological perspective, the researcher's position "is the most important component in defining a methodology" (Crouch & Pearce, 2012, p. 56). According to this the research problem is defined by the chosen research approach and the methods chosen (Walter, 2006). The researcher's position is that an objective description of living walls and their environmental and social benefits exists. This is a traditional objectivist epistemology according to which "knowledge is based on some reality that is external to the learner" (Jonassen, 1990, p. 32). This objective reality can be understood theoretically, but the complexity of the living wall system, the lack of tools to fully model this living technology, and the lack of real-world examples and experience all combine to make that reality unreachable. Moreover, living walls are highly dynamic and their properties and behaviour can change over time, which moves the reality even further from achievable knowledge. In that sense, the reality is believed to be out there but it is only partly accessible, as it is so complex and dynamic.

The objectivist epistemology assumes that there is one objective reality. However, subjective perception is important in this work for two reasons: The first is the assumption that any knowledge is subjective, at least to some extent, and the second is that subjective meanings reflect objective meanings, and subjective meanings are valuable on that basis. Some argue that objectivism "makes people's everyday understandings inferior, epistemologically, to more scientific understandings" (Crotty, 1998, p. 16). However, when assessing living walls' contribution to human wellbeing, for example, living wall users' subjective opinion of their wellbeing would be no less important than would, perhaps, an objective report of their absenteeism rate. In a similar manner, assessing usability can be accomplished by using the living walls and describing the experience as well as by measuring ergonomic parameters.

To be sure, although this work is based on objectivism, it is far from being purely positivist. It addresses the interaction between living walls' vegetation and human life from the perspective that the influence on people is a reality that can only be fully understood subjectively and in context. It is also assumed that the success of a living wall artefact very much depends on both the designer's perception and on the social context of the building and the living wall. Accordingly, the "reality" is believed to be both contextual and social.

3.2.4 Post-positivist theoretical lens

Because it is only possible to reach closer to objective reality using approximations, subjective accounts, and contextual considerations, a post-positivist *theoretical lens* (Crotty, 1998) or *research paradigm* (Blaikie, 2009) was employed for this research. Post-positivism is linked to empirical science (as is positivism), but it is "a humbler version of the scientific approach, one that no longer claims an epistemologically or metaphysically privileged position…" (Crotty, 1998, p. 40). According to post-positivist tenets, even when the researcher adheres faithfully to scientific methods, "research outcomes are neither totally objective nor unquestionably certain" (Crotty, 1998, p. 40). Post-positivism recognises the inherent subjectivity of empirical research and advocates for reflection on the research position to improve objectivity (Crouch & Pearce, 2012). The belief that a post-positivist paradigm is a suitable lens for this work is based on two assumptions: that understanding the design process of living walls for environmental and social benefits is not currently an achievable goal, and that the topic is complex, novel, and multidisciplinary.

3.2.5 Research outcomes

Returning to the subject of this study's outcomes, the post-positivist lens acknowledges that a single "correct" design solution to a design problem is not achievable. "There are thus no optimal solutions to design problems but rather a whole range of acceptable solutions … each likely to prove more or less satisfactory" (Lawson, 2014, p. 90). In the case of living walls, even when defining a specific design problem with detailed performance criteria, the complexity and subjectivity of assessment could lead to several successful designs. As positive development notes, to attain a design with positive social and environmental impacts, the process should be collaborative, interdisciplinary, and holistic (Birkeland, 2008, p. 278). Support for such a design process should thus be suggestive, rather than closed-ended and rigid, to facilitate an increase in the social and natural capital that could be generated by exploring a wider range of options (Birkeland, 2008, p. 96). Given this, the support generated as an outcome of this research is expected to inform designers of numerous potential ways to improve living walls' performance. These possibilities include a detailed description of living walls together with their performance parameters, context and design parameters, and the dynamics of performance improvement.

In other words, the underlying premise is that living walls can enhance urban sustainability, and this study describes the dynamics that may improve this anticipated enhancement. Living walls' sustainability enhancement has not been proven, but it is understood that proof is not feasible given the state of our current tools and knowledge. Moreover, it is also understood that any proof of living walls' potential contribution to sustainability will necessarily be somewhat narrow and will depend significantly on the specific context and parameters. Such specific analyses will unavoidably neglect some important advantages living walls can supply (e.g., eco-system services; see Chapter 2). The decision was thus made to concentrate upon how to enhance the environmental and social benefits of living walls. Equipped with information regarding these dynamics, designers can envision creative living walls that improve environmental and social benefits.

3.3 Research Strategy for a Performance-Based Design Problem

As discussed in section 3.2, the expected outcome of this work (support for more effective and creative living wall design) can be achieved by significantly extending our body of knowledge about living walls dynamics. This segment outlines the research strategy that can generate that knowledge.

3.3.1 Performance-based design problem

A design problem is characterized by a set of requirements such that, should the design propose an artefact that satisfies the requirements, the problem is considered to be solved (Mostow, 1985). These requirements can be related to boundaries, functions, performance, and more, where performance refers to the competence of the desired artefact to function well (Braha & Maimon, 1997). Accordingly, the three research questions developed for this work were devised to identify the design parameters, the performance parameters, and the relationships between them. These questions investigate the connection between the design of a living wall and its performance (i.e., its functional fitness). The causality-based connection between form and function is the basis of many design paradigms, described succinctly by the well-known phrase, *form follows function*. Note that *form* is here understood to represent the set of design decisions, and that one could substitute the word *performance* for *function*. Kalay (1999) argues that the relationship between form and function are not causality-based but context-based, claiming that, for example, different forms can achieve similar functions and highlighting the importance of the role that physical, social, and cultural context plays. Nevertheless, there is consensus regarding the criticality of the relationship between design decisions and performance with respect to guiding design. Performance in the context of design problems was suggested to be "a measure of the confluence of Form, Function and Context" (Kalay, 1999, p. 400). Kalay uses the well-established terms of *form* and *function* together with *context* and advocates combining the three to measure the success of the design. Living walls can assume all kinds of forms (determined by design) and a set of contexts (i.e., their environments) and functions (i.e., the potential social and environmental benefits). Congruent with Kalay's ideas, the design of a living wall should be measured for performance by the extent of coordination between the design, the context, and the functions that the living wall is supposed to perform. The term *performance-based design* was coined to express that notion.

In the context of architectural design, building performance is the factor that guides performance-based design (Oxman, 2008). Thus, the design is led by the success of the living wall to perform according to predefined performance criteria, which are then used when a performance assessment is carried out. In mathematical terms, a *'score function'* should translate the design's functionality (within its context) into a score, or a success rate. The *performance-based design* term is usually used when the score function is mathematically computable. A prime example in architectural engineering is when the design of a building is measured by its resilience to seismic events.

In this work, the performance parameters were identified and defined differently for each of the three studies (e.g., thermal building energy savings for the third study). In other words, this research sought to explore the relationships between the design of living walls and their performance using a range of design, context, and performance parameters. The way to explore these relationships is set by parametric thinking.

3.3.2 Parametric thinking to match the research problem

The parametric study approach, which purports to uncover the most influential parameters and then to describe their influence (Bremault, Driver, & Grondin, 2008), guided the way the relationships between design, context, and performance were understood. According to Rittel, the central difficulty facing design is "to construct a system of functional relationships which connect" design parameters, context parameters, and performance parameters with each other (1971, p. 22). *Parametric design* is a term used to describe a type of design process based on parametric thinking, wherein design problems are first translated into a parametric model such that the relationships between the parameters can then be understood.

Love (2009) divided the adoption of parametric design into two. On the one hand, parametric design tools are used for "gee-whiz form-making," (para. 1) while at the other hand, the same technology expedites "a metric-based emphasis on social and/or ecological relevance" (para. 5). Parametric design tools were not involved at all in this research, but the concept of translating the problem into a parametric model and studying the model using its parameters was illuminating. The term *parametric design* "implies the use of parameters to define a form when what is actually in play is the use of relations" (Monedero, 2000, p. 371). These relations were the main object of inquiry in this study, since its purpose was to understand the relationships between design parameters and performance.

Parametric design requires that a parametric model of the design problem be built. This process is characterised by abstract thinking and requires the parametric model to be applicable in new situations and to depend on essential inputs (Woodbury, 2010). Woodbury adds that "abstraction is the hardest new skill for designers ... it involves thinking more like a computer scientist than a designer" (Woodbury, 2010, p. 185). Rittel's 1971 model of parametric design discusses instrumental knowledge that relates to three kinds of entities, which can be described as variables. In this research, the term *parameter was* used in place of the term *variables*. Such parameters can assume different values and were adapted to the current study in the following manner:

- Performance parameters—outcomes that can be measured and by which the living wall was evaluated;
- Design parameters—the living wall designer's range of choices; and
- Context parameters—factors that affect the living wall design that are not controlled by the designer.

The causality-based relationship between the design of an object in a specific context and its resulting performance can be represented mathematically as it is below, where ***p*** stands for performance, ***d*** for design, and ***c*** for context (Rittel, 1971).

$$p=f(d,c)$$

However, Rittel's equation does not reflect the multi-dimensionality and complexity that living walls represent. For a specific living wall project, the performance ***p*** is a vector of values (not necessarily numeric) that reflects the performance parameters. Similarly, ***d*** and ***c*** are both vectors of values of the various design and context parameters. A more explicit form of that equation would then be

$$(p_1,p_2,\ldots,p_n)=f((d_1, d_2,\ldots, d_m),(c_1, c_2,\ldots c_l))$$

The mathematical function ***f*** describes the relationship between design, context, and performance. Inspired by the concept of system dynamics in general systems theory (see section 3.2.1), this function is an abstract representation of what this work defined as "living wall dynamics."

One of the fundamental steps in any design research project is to identify and define the relevant performance criteria (Blessing & Chakrabarti, 2009). The designer constructs an evaluation system that includes identifying the relevant performance parameters and their relative importance, and then constructs a measure of overall performance to evaluate alternate solutions (Rittel, 1971). As this process applies to this research, the designer should identify the measures of the living wall's performance in terms of environmental and social benefits. The designer should also anticipate the context of the living wall (defined by its context parameters) and identify a relevant solution space (determined by the set of design parameters). The next step is to restrict the solution space by identifying constraints such as limits to parameter values and relationships between design parameters. The central difficulty of designing, according to Rittel, is to construct a model of the object (in this case, living walls) that reflects a system of functional relationships that connect design parameters, context parameters, and performance parameters with each other (see Figure 3.1). This task formed a major part of this research.

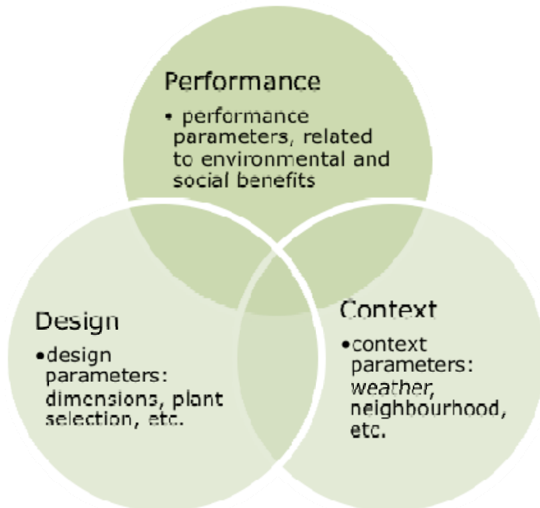

Figure 3.1. Living wall dynamics–relationship between design, context, and performance

The above segment summarises why parametric thinking so appropriately influenced the methodology used, given that the research questions in this research were related to design and performance parameters and to the relationships between them. Parametric research facilitates the study of those relationships, identifying patterns of how changes in a specific parameter influence a specific performance criterion. In other words, it allows us to study living wall dynamics.

3.3.3 Inductive inference: Finding generalisations and patterns

Blaikie (2009) discussed how the ontology and epistemology of the research, as well as the types of research questions, influence the strategy by which the research questions are answered. He presented four research strategies that are relevant to social research, and the inductive, deductive, retroductive, and abductive strategies are discussed here briefly to explain why the approach taken in this study was the best choice possible.

The goal of researchers using the retroductive research strategy is to "discover underlying mechanisms that, in particular contexts, explain observed regularities" *(Blaikie, 2009, p. 87)*. However, this study's goal is to describe regularities, rather than to understand their underlying mechanisms. Within its scope, as long as a designer can replicate the success of a living wall by making certain design decisions, it is not critically important to understand why those choices work—*i*t is enough to correctly identify that they enhance performance.

Similarly, the deductive strategy is not relevant to this study, since no hypotheses are tested. The deductive strategy is suitable when the aim is to hypothesise and then test those hypotheses in order to eliminate any false ones. This work describes patterns such as this: *When a living wall in Tel-Aviv has substrate thickness of 6 cm or more, it significantly improves the building's cooling capacity, thus reducing energy consumption*. The thermal processes that occur in the complex interactions between the substrate, the building, and the environment are not the focus of this research.

This research essentially generalised data points into meaningful patterns, and inductive reasoning is the most direct way to make such generalisations. Induction can take two forms:

- enumerative induction, where a generalisation is made from a sample or samples to a general property; and
- explanatory induction, where a reasoning is developed from data to a causal hypothesis *(Atocha, 2006)*.

The reasoning that typifies this research is, first and foremost, enumerative induction, wherein a set of data points is clustered to form a generalisation. Explanatory induction reasoning was also used in this research, but to describe the part it plays, we must first discuss the fourth research strategy: abduction. The abductive strategy that Blaikie described is very specific to social research questions, as it is based on understanding social life by iteratively developing theory from everyday lay concepts *(Blaikie, 2009).* Given the relatively minor role that social science plays in this research, such iterative development is only somewhat relevant to this research. However, abductive strategy is attributed to other fields of research in a more general sense:

> Abductive efforts seek some [new] order, but they do not aim at the construction of any order, but at the discovery of an order which fits the surprising facts; or, more precisely, which solves the practical

problems that arise from these. (Reichertz, 2009)

The term abduction as a type of intellectual reasoning was coined by Peirce (1932), and it can be succinctly described as reasoning from effects to causes: "The surprising fact, C, is observed; But if A were true, C would be a matter of course. Hence, there is reason to suspect that A is true" (Peirce, 1932).

However, the literature generally exhibits some confusion and overlap between abduction and induction *(Atocha, 2006)*. For example, in the field of artificial intelligence, the term *induction* is used to describe the process of learning from examples, but it is also used to produce a theory to explain the observations. In other words, the term *abduction* can be considered an instance of induction. Some have noted that there are several incompatible ways to perceive the relation between abduction and induction (Flach & Kakas, 2000) and that, in some situations, it is more appropriate to distinguish between induction and abduction, while it is more appropriate to unify them in others.

Atocha (2006) offers the following clarification: "Abduction is usually restricted to producing abductive explanations in the form of facts. When the explanations are rules, it is regarded as part of induction." (p. 34) She goes on to say that abduction explains a single observation, whereas induction explains a set of observations and predicts further observations. It is also interesting to note that both induction and abduction are characterised as *non-monotonic* inference types, which means that new premises might invalidate a previous argument.

Having thus defined the various research strategy possibilities, it is noted that this research, using samples gathered from the living walls data, employed enumerative induction to produce generalisations about the influence of design decisions. Some abductive reasoning was also employed, however, especially in the food production and survey studies where the explanatory process was required in order to identify the studied parameters and in order to find patterns in the data. For example, it was noted that smaller plants grew in systems with small substrate compartments. Abductive reasoning lead to the assumption that root volume limited the size of the plants. The parameter of root volume was thus identified as one of the design parameters studied and, during the analysis stage, the productivity of each living wall system was compared to the available root volume per plant. This kind of reasoning suggested an explanation to a surprising fact via abductive reasoning, and then to using more samples and more inductive reasoning to create a rule regarding the root volume for required to sustain productive living walls.

Inductive research strategy, the main logical inference method in this work, allowed for the generation of rules (and predictions) from a set of observations. Abductive strategy was used in a limited fashion when a creative 'leap' was required (for example, when identifying design parameters and performance parameters).

3.3.4 *Using data to describe living wall instances*

The data collected for this research consisted primarily of characteristics (design and context parameter values) and performance (performance parameter values) gathered from many instances of living walls. Represented mathematically, these living wall indicators formed a set of points in a multidimensional space where the dimensions were the characteristics of the living wall and its performance aspects. This is only an approximate description of the type of data that was collected in this research, but the set of living walls studied was not random: some were virtual living walls generated within the simulation software, some were real (non-virtual) prototypes of living walls with characteristics controlled by the research plan, and the remainder were actual living wall projects as their users described them. The outcome of this research—knowledge about the dynamics of living walls—was actually a set of generalisations or patterns that emerged from the data. These generalisations were expected to have the structure of "A living wall with design *D* and context *C* has a performance *P*," or "Changing the value of a design parameter *X* will result in changing the performance parameter value *Y*." The knowledge generated was therefore a compilation of generalisations derived from the data set of living walls' design and context parameter values and performance parameter values.

3.4 Translating Parametric Thinking to Research Methods

Translating parametric thinking into research methods typically results in building a digital model of the research topic and using computerised methods (e.g., software simulation) to manipulate parameters and assess the resulting performance. However for this work, computer simulation was somewhat limited. It cannot estimate social aspects, and its ability to handle living plants is limited. In short, computer simulation is better suited to investigating a narrowly defined problem than it is to a holistic research approach. Therefore, computer simulation was not the only method used. Using a survey incorporated the human social aspect, and the living vegetation aspect was addressed by conducting the food production study.

The benefits of using several different research methods is that the various methods' inherent limitations can be countered by the strengths of other methods (Brewer & Hunter, 1989). Multi-method research is holistically oriented and is therefore well suited to research that is "driven by its subject matter" (Reinharz & Davidman, 1992, p. 197), as it is to an interdisciplinary work such as this one. The case study, survey, and thermal simulation methods used in this research were chosen to answer the main research problem—finding patterns in the relationship between the design of living walls and their performance.

The first research question was answered by a parametric analysis of the case study of living wall systems. Several aspects of the living walls' performance (e.g., food production) were measured and correlated with the living wall systems' characteristics. A parametric analysis of the survey results revealed patterns in how the design and context of living walls are correlated with their performance, as perceived by the users, to address the second research question.

The third research question was resolved using a parametric simulation study that revealed patterns in the influence of living wall design parameters on building energy consumption in two different climates (see Table 3.1).

Table 3.1. Research methods used for addressing the research questions

	Research Questions	Methods
RQ1	In what ways do different living wall systems relate to edible living wall performance?	Case study
RQ2	In what ways do living wall context and design parameter values relate to their performance, from the users' point of view?	Survey
RQ3	In what ways do living wall design parameter values relate to buildings' energy consumption?	Simulation

The methods used in this research constituted different ways to collect data for parametric study: In the food production study, design parameters were either actively changed by creating new designs and new plants or by changing conditions, or they were passively changed by observing the appearance of walls with different parameter values. In the survey method, data regarding design and context parameter values was collected and correlated with the user-perceived performance of the living walls. The parameter values of the living wall model were modified in the thermal simulation study and the different performance results were then analysed to find patterns. See Figure 3.2 for a map of the design, context, and performance parameters incorporated in each of the three analyses. The next section discusses how the three studies were systematically and rigorously designed.

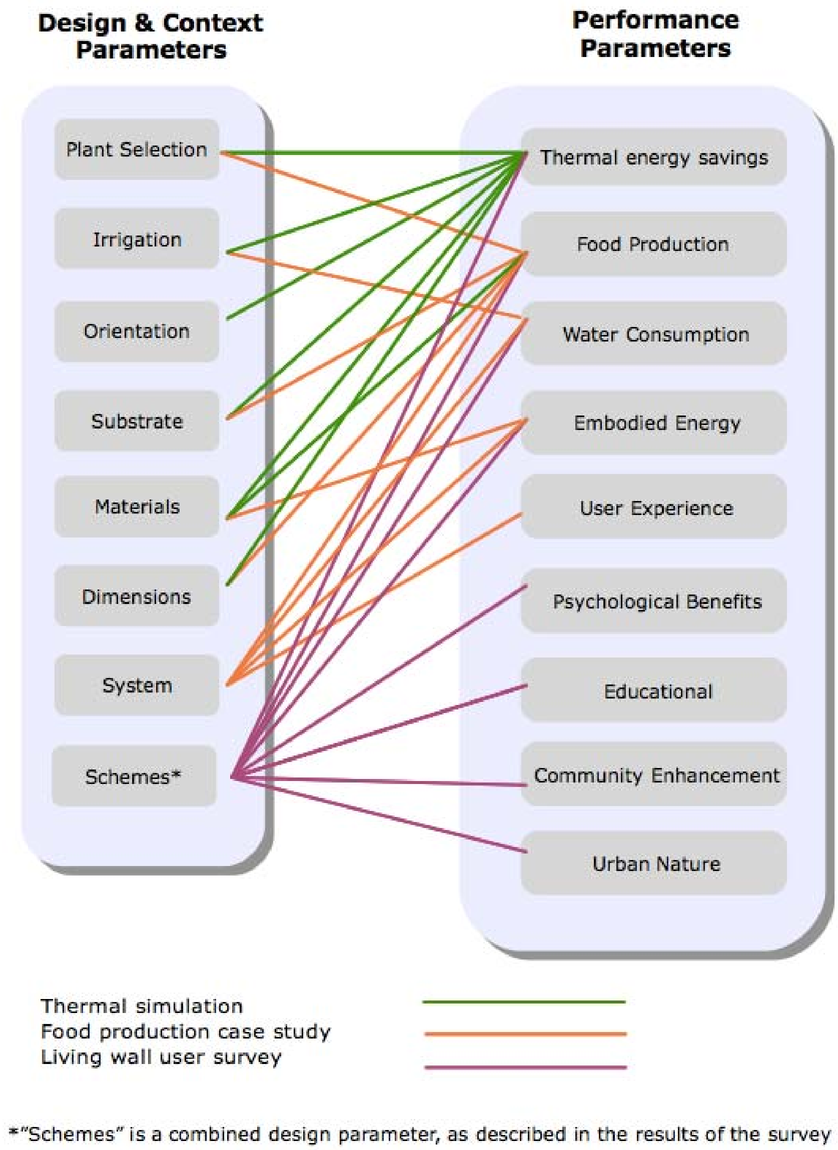

Figure 3.2. Map of the living wall parameters and performance parameters covered by each of the three studies

3.4.1 Parametric study via prototyping and case studies

Computer simulation could not simulate the living vegetation that was a significant factor in the food production study. It was therefore essential to use an empirical research method that was based on real-life scenarios. However, running a full scale (agronomic) experiment with enough parameter values and repetitions would require a massive amount of resources and more vertical space than is readily available in an urban context, and certainly not in an urban household context. The decision to use a case study approach was made to limit the scope of the study "so that its boundaries are explicit and the project feasible" (Crouch & Pearce, 2012, p. 124). In case study research, the scope is a specific and bounded system, and the focus is on choosing and defining the "case" (Stake & Munson, 2008).

One of an experiment's chief characteristics is that it is based on separating a phenomenon from its context (Yin, 2003) and then narrowing that phenomenon down to specific variables. Context played an important role in this study, given that the border between the context parameters and the design parameters was not very well demarcated to begin with. Case study is defined as an empirical inquiry that is particularly suitable when "the boundaries between phenomenon and context may not be clearly evident" (Yin, 2003, p. 16), thus this method seemed appropriate.

Since there are so few real-life instances of vertical urban farming, defining the cases for the study either by using existing vertical gardening systems or by prototyping custom systems in a domestic context was preferred. The design of the food production study required setting up systems for an empirical study, as well as prototyping systems before and during the study. In the food production study, each case was a specific living wall system within an urban household setting that was used to grow food year round.

Another aspect of the food production study was the sheer number of interesting living-wall-system parameters involved: their physical properties, their positioning, the plants and vegetables grown in them, the surrounding microclimate, and so on. Nonetheless, the amount of relevant data points was limited. Case study inquiry handles exactly this type of situation (Yin, 2003).

In this research, each design parameter was first identified; then the range of feasible values of the parameter were observed and/or created; any measurable performance parameters were identified; and finally, the results were analysed in a comparative manner to assess the connection between design parameter values and performance results.

Two important methodological traits should also be noted: First, the researcher's farm-related experience was typical of most laypersons (i.e., rudimentary at best), and secondly, the experimental wall trials were set up in a typical urban backyard. This created a context that generated applicable research conclusions and results that could enhance practical use. Given limited resources, it facilitated holistic inquiry and understanding, and exhibited a multitude of design considerations. Nevertheless, due to the limited amount of data points (a situation typical of most case studies), this study's recommendations were based on analytic, rather than statistical, generalisations.

3.4.2 Parametric study via user survey

The second method used looked for patterns in the way living walls' design parameters influence their performance as their users perceive them. To understand the range of user opinions, a survey was conducted among living wall users. The data collected in the survey was largely quantitative, which facilitated quantitative analysis.

Design and context parameters were the original parameters studied, but a new emergent parameter was discovered as part of the data analysis process (denoted here as *design scheme* or *scheme*) that actually combined a group of design and context parameters. In addition to the comparative analysis of perceived performance according to design parameter values, the scheme parameter allowed a practical reduction in the amount of parameters, which in turn allowed to extract valuable patterns regarding the relationship between the scheme of a living wall and its perceived performance.

3.4.3 Parametric study via energy simulation

Building simulation programs "allow architects and engineers to test out new designs before proceeding to construction and installation" (Hong, Chou, & Bong, 2000). However, there are very few extant living walls, and if this research had included only living wall projects that exhibited significant thermal benefits, the number of cases would have been even fewer.

Further, empiric parametric study of thermal performance would have been almost impossible with the time and resources available, even if enough examples could have been found. It was not reasonable to cover hundreds of buildings or building living wall walls with various parameter value combinations. Therefore, this study used thermal energy simulation software that allowed for the manipulation of many living wall design parameters and the recording of the influence of that manipulation on thermal performance.

Note that although this study is quite narrow in the sense that it focuses on only a single performance criterion (building thermal energy), the ease of applying various values to the design parameters allowed the incorporation of a broad set of data points. That said, software limitations restricted the characteristics of the virtual living walls that were studied. The specifications and limitations of this study are explicated in the methods chapter.

3.5 Summary of Methodology

The methodology used in this research emerged from the premise that living walls can potentially offer significant social and environmental benefits, thus contributing to urban sustainability. Owing to the critical role that design plays in achieving sustainability, the aim of this work was to generate support for improved living wall design.

It was also determined that it is not possible to arrive at a complete, detailed understanding of the relationship between performance and living wall design decisions (living wall dynamics) owing to the complexity of the topic, the importance of subjective knowledge, and the problems inherent in measuring living wall sustainability. Consequently, this research focused on holistically understanding the core knowledge, which constitutes living wall dynamics.

Accordingly, the research problem was constructed as a performance-based design inquiry, and parametric thinking was chosen to induce generalisations regarding the influence various design and context parameters would have on living walls' performance. Parametric thinking was translated into three different methods that were used in the studies conducted as part of this research: case studies for parametrically studying edible living walls' performance, a user survey for parametrically studying the performance of living walls as perceived by their users, and energy simulation for parametrically studying thermal performance. The next chapter describes how each of these methods was used in the three studies.

4 Three Methods for Parametric Studies

Prior chapters explained why parametric study was chosen to study the relationships between living wall design and performance. This chapter describes the methods used to conduct the three types of parametric studies. Each used a different method to address the research objectives: mapping design decisions, mapping type and extent of performance, and describing the relationships between design and performance. Each study focused on a different set of design parameters and performance parameters in order to answer one of the three specific research questions and thus cover the principal gaps identified in in the current body of knowledge about living walls.

4.1 Edible Living Wall Case Study of Selected Living Wall Systems

One of the largest gaps identified was related to living walls that are used for agriculture—*edible* living walls (see Table 2.1). To enhance knowledge related to edible living walls and to the relationship between their design decisions and their performance, a physical study of domestic living wall systems that grow edibles was developed using six different living wall systems and diverse plant species.

The edible living wall case study was designed to identify the design decisions related to living walls and thus expand design-parameters knowledge that is relevant for both this and the following studies. The following were its operational objectives:

1. identify design parameters relevant to the six living wall systems;
2. describe each system's productivity, water consumption, embodied energy, and user experience; and
3. compare systems according to the four performance parameters: food production, water efficiency, embodied energy, and user experience.

Each living wall system was considered a separate case of living wall design within the case study, and they were studied concurrently.

4.1.1 Timeline and chronological stages

The following steps were undertaken during the study:

Pilot Stage: After setting up four types of available living wall systems, a short period of assessment (from August through November, 2011) was devoted to identifying living wall design parameters and defining the performance parameters that were measured in this study.

Design of New Systems: From October, 2011, through April, 2012, new living wall systems were designed and constructed to improve upon the initial renditions. Several prototypes were developed and tested. Two new systems were eventually added to the study: planting pockets sewn from various synthetic textiles/sheets ("Invivo Triple Pocket" system) and a system made from reclaimed wooden pallets and used flour bags ("Reclaimed Pallet" system).

Observation and Evaluation: From the time the first living wall systems were set up in August 2011 until December 2012, seedlings of various kinds of vegetables were planted in the living wall systems. These vegetables were monitored daily, and they were regularly pruned and harvested, and then replanted where necessary. The observation process included maintaining a photographed log of all crops harvested, irrigation schedules, and a diary of observations. See section 4.2.5 for details regarding productivity measurement and the harvest log.

Drip irrigation was used for the various living wall systems, and each system had an automatic irrigation program. The irrigation system included a container with organic liquid fertiliser that added nutrients to the water. The irrigation computer allowed for six different irrigation schedules to enable full flexibility in adjusting the amount and frequency of irrigation to each specific living wall system. Irrigation schedules were set and adjusted per living wall system by inspecting moisture in the growing substrate and noting any excess water. Details of the adjusted irrigation schedules per system are presented in the results chapter. Plant species were selected according to their ability to produce edible crops (e.g., lettuce, basil, tomato). Germination trays were used to prepare seedlings for some of the vegetables. Other seedlings were bought as tube-stock from a local organic vegetable nursery, located about 20 kilometres north of Tel-Aviv.

4.1.2 Location for edible living walls in Tel-Aviv

A residential neighbourhood in Tel-Aviv, Israel (Hadar-Yosef) was chosen as the study site. The city of Tel Aviv, Israel, located at 32°06′ N 34°47′ E, has a Mediterranean climate (‘Csa’ according to Koppen climate classification). During summer, the daily average temperatures are around 22.2°C - 29.0°C, while daily average relative humidity is around 61 – 83 percent (Potchter, 2006).

The block where the study was located included 10 buildings comprising 40 townhouse-style units. Using GIS data from Tel-Aviv’s city council (Tel Aviv Municipality GIS, n.d.), the area of available vertical surfaces in the block was calculated. Layers of photography as well as street names and numbers were used and are presented in Figure 4.1. A ‘measure’ tool was used to take both length and area measurements. After accounting for the fences between the buildings and the area of building envelopes, a total of more than 3,500 square meters of vertical area was available for accessible living walls. Some of this area may be shaded, and might require living walls based on shade-loving plants. All of this area was between 30 and 200 centimetres from ground level. Vertical surfaces that were below or above this height were not included in the calculation. The ground area of that block was 7,116 square metres.

Figure 4.1: Residential block in Tel-Aviv, Hadar-Yosef neighbourhood (text in Hebrew) from the Tel-Aviv municipality GIS system, showing block layout and total ground area

This means that in this neighbourhood, for each 1,000 square meters of area used for residential use, 500 square meters of vertical surface could be covered with accessible living walls without altering the area’s existing land use.

This study’s location allowed frequent daily accessibility and was characterised by a large, equatorial-facing fence. Five living wall systems covered the long fence on the border between the private yard and a lane. One additional living wall system (the Reclaimed Pallet system) was constructed on the east border of the yard to form part of a low fence separating the owner's yard from a neighbour's. This was the only living wall system that did not cover the equatorial-facing fence. The only shading relevant for the living walls studied was from two young trees that blocked some of the sun for not more than 2 hours a day in summer, while sun exposure was approximately 10 hours a day. Germination trays that were used to prepare seedlings were embedded in a polar-facing fence.

4.1.3 Six living wall systems

The living wall systems that were studied combined four commercially available products and two systems that were designed and produced during the study's pilot stage. The following systems were selected to represent a variety of materials, sizes, and morphologies:

1. Three Woolly Pocket "Wally Three" planters (Woolly Pocket, n.d.);
2. Ten Invivo "Triple Pocket" (Invivo Design, 2015);
3. Six Evo Organic "Aria" vertical planting units (discontinued)
4. Twelve ELT "Easy Green" living wall panels (ELT, n.d.);
5. Sixteen Invivo "Domino" planters (discontinued); and
6. One vertical bed constructed from reclaimed pallets.

An overview of the first five systems on the fence is shown in Figure 4.2.

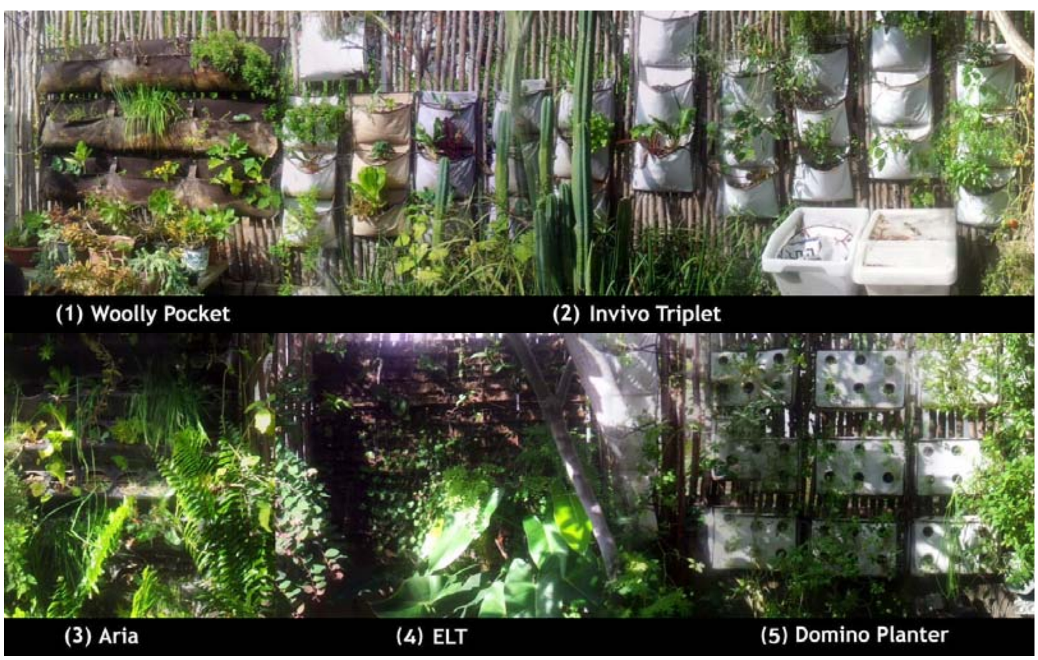

Figure 4.2: Photo depicting five of the six systems used for the living wall case study. (1) Woolly Pocket's Wally Three, (2) Invivo Triple Pocket, (3) Evo Organic's Aria, (4) ELT's Easy Green, and (5) Invivo's Domino planter

The Woolly Pocket, Wally Three planting products (ordered from the U.S. via the company's website) were made of thick synthetic felt. Each unit was 172 centimetres long by 38 centimetres high and contained nearly 34 litres of growing substrate (Figure 4.3).

Figure 4.2: The Woolly Pocket system (3 units depicted here) are elongated planting pockets made of thick synthetic felt.

The Invivo Triple Pockets (Figure 4.4) were designed and manufactured locally during the pilot stage. Each of these 10 units featured 3 connected planting pockets made of PE or PVC/PE sheets. Each was 100 centimetres high by 40 centimetres wide and held 8 litres of growing substrate per pocket, thus totalling 24 litres per unit.

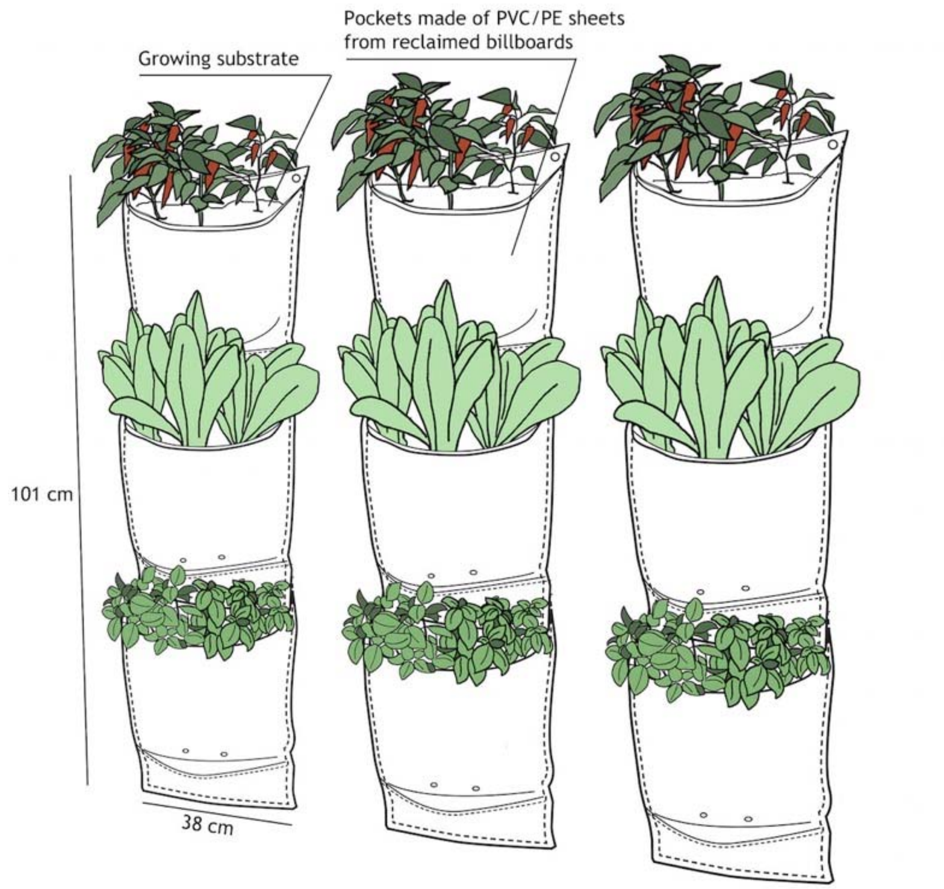

Figure 4.3: Three Invivo Triple Pockets made of reclaimed billboard ads

Evo Organic's Aria units (Figure 4.5) were ordered from the U.S. via the company's website. These 6 rigid panels were made of high density polyethylene (HDPE). Each unit was 60 centimetres wide by 67 centimetres high, and contained 36 litres of growing substrate.

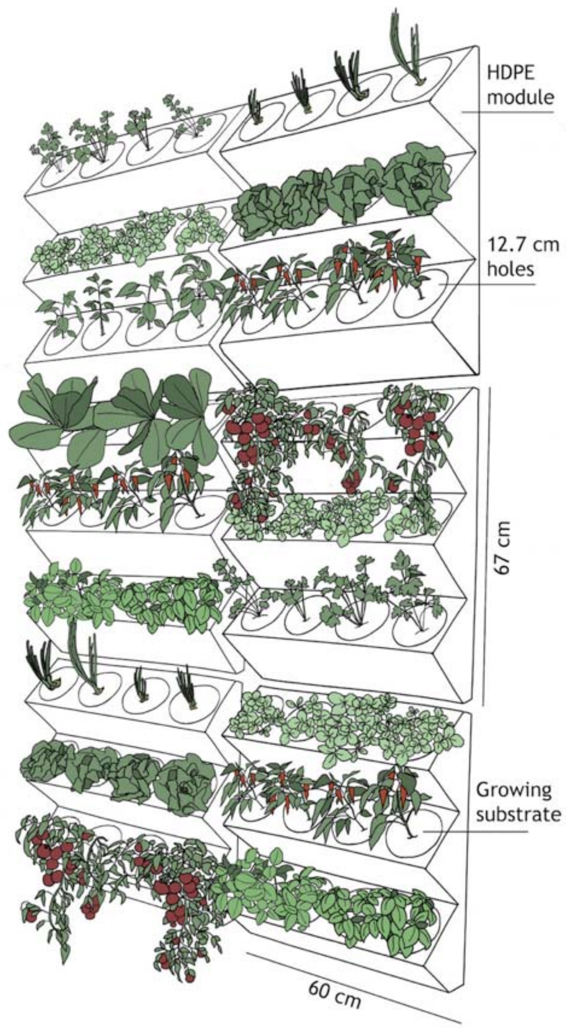

Figure 4.4: Six Aria vertical planting units made of HDPE

ELT's Easy Green living wall panels (Figure 4.6) were ordered from Canada via the company's website. These twelve rigid panels were made of high density polyethylene (HDPE). Each of the units was 30 centimetres wide by 30 centimetres high and contained 9.5 litres of growing substrate.

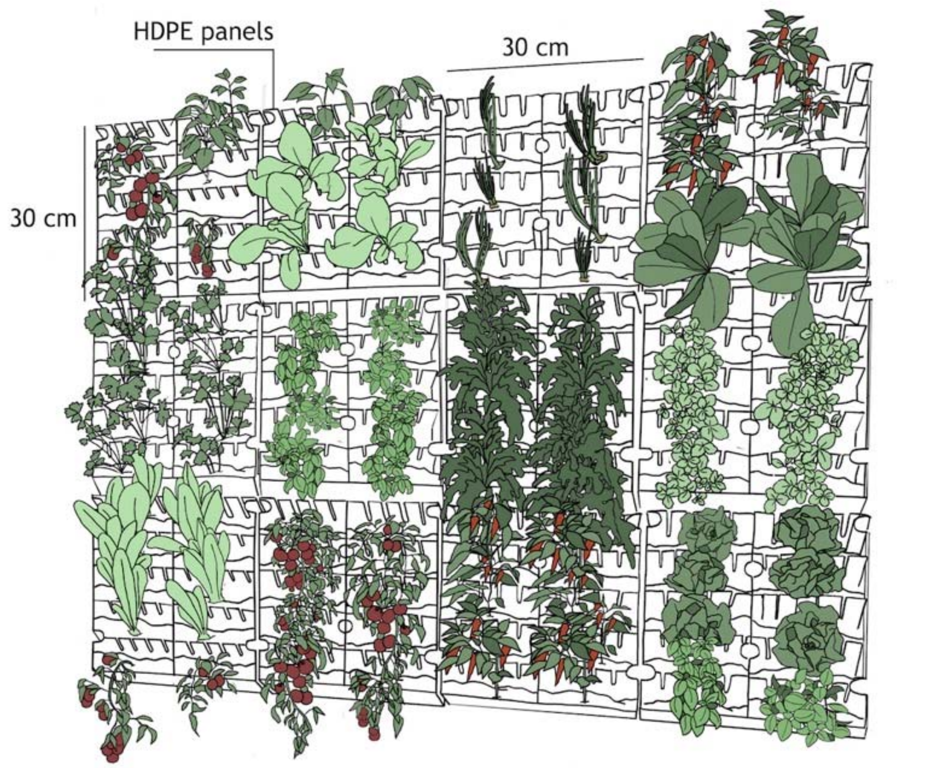

Figure 4.5: Twelve Easy Green panels by ELT made of HDPE

The Domino planters (Figure 4.7) were produced by the Invivo Design Studio using polyethylene (PE) sheets. The sheets covered blocks of Fytocell® foam that were ordered from the Netherlands. These sixteen planters were 45 centimetres wide by 30 centimetres high, and each contained 9.4 litres of the Fytocell growing substrate.

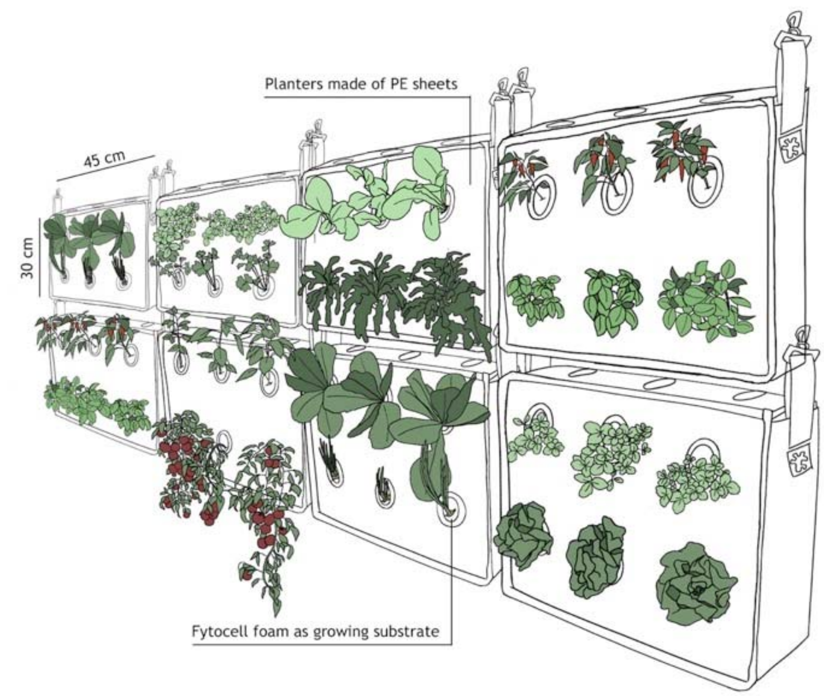

Figure 4.6: Eight Domino planters (out of 12) made of PE sheets covering Fytocell foam

The Reclaimed Pallet system (Figure 4.8) was constructed during the pilot stage of this study. The system was made of two reclaimed wooden pallets, each holding three used flour bags that contained the growing substrate. The pallet's dimensions were 110 centimetres wide by 110 centimetres high and 14 centimetres deep. It contained approximately 120 litres of substrate.

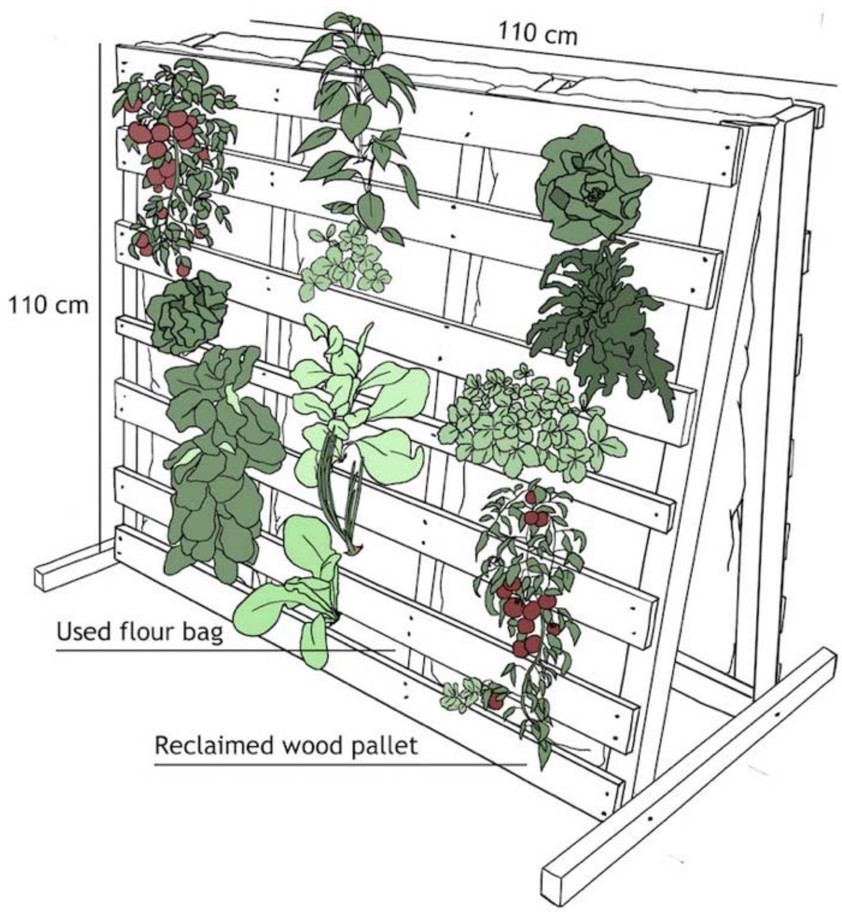

Figure 4.7: Reclaimed Pallet system holding three used flour bags filled with growing substrate

4.1.4 Identifying design parameters for edible living walls

During the planning stage, design parameters pertaining to edible living walls were identified. Some design parameters were added during the pilot stage (see section 4.1.1) and more additions were made during the observation and evaluation stage. Commercially available living wall systems were chosen and purchased. Considerations for choosing living wall products were that the systems had variable morphologies and were made of assorted materials. This resulted in diversity in the systems' dimensions, materials, manufacturing processes, transportation, longevity, and end-of-life disposal. The values for these parameters were recorded for each system.

The planting plan designated the types of edible plants, as well as whether they were grown from as seeds or seedlings. According to Zhu et al. (2000) "both theory and observation indicate that genetic heterogeneity provides greater disease suppression". Thus, the food production goal benefited twofold from adopting a heterocultural slant. First, the food grown is more diverse, and yields are harvested continuously rather than in bursts. Secondly, the crop's heterogeneity renders it inherently more resistant, thus reducing the need for pesticides and increasing its survival capacity.

The vegetable planting plan included these species categorisation:

- leaf vegetables: lettuce, chard, celery, rocket, fennel, mizuna;
- herbs: parsley, mint, sage, oregano, basil, rosemary, stevia, lemon grass, spring onion, chives;
- brassicas: cabbage, kohlrabi, cauliflower, kale;
- root vegetables: carrot, radish, beetroot;
- fruit vegetables: tomato, eggplant, zucchini, peppers, chilli, melon, watermelon, squash;
- legumes: soy bean, pinto bean, snake bean; and
- maize.

The above plant species were grown in all available systems but for maize that was only grown at the top of the reclaimed pallet system, and the large fruit vegetables (melon, watermelon, and squash) that were grown only at the bottom of the Reclaimed Pallet system, in order for them to get support from the ground.

During the setup stage, the living wall systems were hung and filled with growing substrate (all but the Domino planters arrived empty and required the growing substrate to be added). The volume and weight of the growing substrate that was used to fill the living wall systems was measured and then recorded as one of the design parameters for each system. During setup, significant differences were noticed in the volume available for roots between systems. In some, the substrate volume was shared by several plants (e.g., the pallet system contained 40 litres of substrate volume for 6 plants), while in other systems, each plant was allocated a constrained volume of growing substrate (e.g., the Invivo pocket system offered 8 litres per plant). Available root volume per plant and the compartmentalisation of root volume was recorded for each system and correlated with productivity.

Plant spacing was another parameter that varied between living wall systems. It was determined by the design of some of the living wall systems. For example, the Domino planter allowed 15 centimetres between plants, while other systems accommodated more flexible spacing (the Woolly Pocket's 55 cm was shared by 1–3 plants).

The final step was installing irrigation. Although all the living wall systems used an automated drip irrigation system, the number of emitters and the irrigation's duration and timing were determined according to the size of the living wall and the number of plants per area. Irrigation parameters were adjusted during the growing period to achieve maximum substrate water capacity with minimal excess. Irrigation for all systems was turned off manually only on a few rainy days when it was obvious that water are already in excess for all systems.

An additional design parameter identified was the angle of the planting surface. A horizontal planting angle (0º), traditionally used for planting in the ground, was well-matched to the pocket-type planters, whereas a vertical planting angle (90º) suited the Domino planters and the ELT system. Systems with interim values were the Aria system (at 30º) and the Reclaimed Pallet system (at 70º), as their planting surface is slanted (see Figure 4.9). Similar plants were tested on systems with different planting angles, and the results were compared.

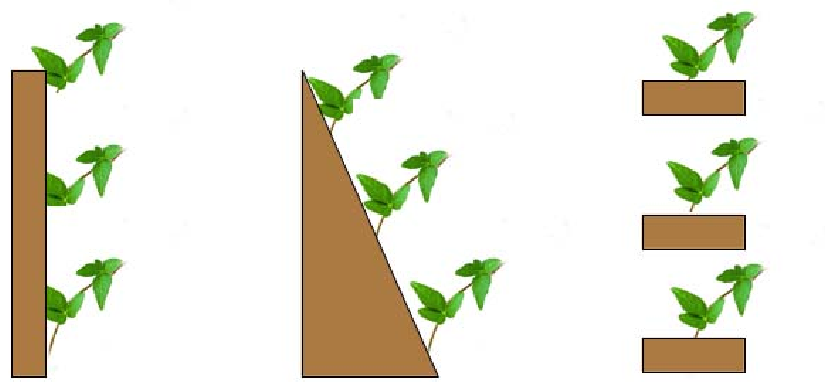

Figure 4.8: Demonstrating three optional values to the planting angle parameter

The porosity of the living wall material influenced both the moisture content inside the systems and their aesthetics. The height of the system was also noted as a significant parameter affecting the living wall's ease of use, as well as the distance of the system from ground level parameter. The last parameter that emerged during the study was the stability of the growing substrate of the living wall, as it modified the experience of re-planting or rooting a plant.

In summary, the following design parameters were identified for edible living walls:

- vertical surface orientation (e.g., south, north, south-west, etc.)—the aspect of the building wall covered by the vegetation;
- locality of materials—the location of source materials required to manufacture the living wall;
- manufacturing processes—the type of processes required to manufacture the living wall;
- longevity and end-of-life—the expected longevity of the product and the possibilities for recycling or decomposing it at end-of-life;
- plant selection—the type of vegetables grown according to the categories defined above;

- growing substrate weight—the weight of the growing substrate required to cover a constant wall surface area;
- available root volume per plant—the amount of growing substrate available for each plant;
- spacing between plants—the distance between the vegetables;
- irrigation design and schedule—the irrigation type, output, and schedule;
- planting angle—the angle of the growing substrate where vegetables are planted;
- porosity of materials—the porosity of the materials covering the living wall;
- system height—measured from ground level, as it affected the ease of maintenance;
- distance from earth level—the interval between the living wall and the ground; and
- growing substrate stability—the rigidity of the growing substrate or its tendency to disintegrate when being used.

After establishing the list of relevant design parameters, the influence of each parameter on the performance parameter values was studied to expand the knowledge of living wall dynamics.

4.1.5 Defining performance parameters for edible living walls

The choice of performance parameters was guided by their context: the six case studies were all small living wall systems located on a fence in a domestic urban backyard and operated within a household context. This kind of living wall was not expected to perform in terms of building energy, building protection, runoff modulation, or biodiversity enhancement. Therefore, the first performance parameter that was measured in the scope of this study was food productivity—the amount of vegetables that were grown by each of the studied systems. This performance criterion had not been addressed in any previous research. With respect to human wellbeing, since this was not a public living wall, the only relevant aspect was the user experience of the researcher as the case study was being conducted. User experience here refers to the experience of a person using the living wall with respect to how easy it is to setup and maintain and how pleasing it is to watch.

Additional performance parameters that could be measured were related to living walls costs, specifically the materials and work invested in producing the living wall system and using it through its entire life cycle and the amount of water consumed during the study. These were denoted "embodied energy" and "water efficiency". The next paragraphs describe each of the four performance parameters and the methods used to measure them.

Food productivity was estimated by documenting the harvest from all systems during the year-long study. Living wall systems were harvested frequently (on either a weekly or daily basis, depending on the yield). Harvest type, weight, and originating system were documented as entries in the harvest table. The weight of the harvest was an important determinate needed to perform comparisons and analyses of the living walls' productivity. The portion weighed was always the edible part (i.e., the fruit for fruit vegetables; the roots for root vegetables; leaves and/or stems for herbs and leaf vegetables; and bean pods for legumes).

User experience for the living wall systems was estimated during the study by recording the usability of the systems' setup and maintenance requirements as well as any exceptional difficulties encountered. Appearance-related issues that were recorded during the study also influenced the user experience. The living walls were tended mainly by the researcher, but occasional feedback from visitors was included to offer a more comprehensive perspective.

Water efficiency: Water consumption was measured by the amount of irrigation water required per system. The water efficiency of each system was calculated for the entire year by dividing the total water consumption by the weight of the harvest.

Embodied energy: The materials used by each system were estimated using two criteria: categorising them into recycled, reused, or new, and comparing the distance travelled from the manufacturing site. The manufacturing processes were then categorised into low-, medium-, or high-energy, while the transportation variable was categorised into short (for local manufacturing) and long (for global manufacturing). The expected longevity was estimated based on manufacturers' data. End-of-life was described according to the percentage of product material that could reasonably be recycled/reused/decomposed at the end of the products' lifespan. This estimation did not include a full life cycle analysis (LCA) or a numerical embodied energy calculation, but it did allow for comparison between the living wall systems in terms of their embodied energy.

4.1.6 Summary of the case study method

The edible living wall systems case study was devised to enable real-life assessment of different living walls designs. The study's purpose was to identify design parameters relevant to living walls and to reveal patterns in the relationships between design parameters and the performance of living walls that were used for food production in a domestic urban context. The study was based on six living wall systems that grew edible plants. The pilot stage was followed by a year-long observation and measurement stage, which included documenting and measuring the performance parameters.

During the pilot stage, fourteen relevant design parameters were identified. Four performance parameters were subsequently defined: productivity, user experience, water efficiency, and embodied energy. Each of the performance parameters was recorded per system, and this data was compared between the systems and analysed to reveal the systems' dynamics—the relationships between edible living wall design parameters and their performance.

4.2 Survey of Living Wall User Opinions and Living Wall Schemes

Another significant knowledge gap identified in the literature was the benefits living walls have for human wellbeing (see table 2.1). In order to enhance knowledge related to the impact of living walls on their users, a survey targeted living wall users to collect subjective data regarding the perceived performance of existing living walls. The survey included data regarding living walls' design and context parameter values and their performance ratings, allowing a parametric analysis of the data to uncover the relationships between living wall design and (perceived) performance. The operational objectives of the living wall survey were to:

- map living wall design (parameter values) and context,
- describe the users' reasons for utilising living walls,
- estimate the perceived performance of the living walls according to several performance parameters, and
- find correlations between design parameters (or schemes), the reasons users offered for maintaining the walls, and the walls' performance.

The survey was the main method used to estimate social performance parameters because the performance data originated from a human source (survey).

4.2.1 Characteristics, reasons, and perceived performance

The survey was composed of three parts: The first covered the basic characteristics of the living walls (design and context parameters); the second examined the reasons given for maintaining living walls; and the third encompassed their performance as perceived by the users (see Appendix A).

Living wall characteristics included the walls' dimensions, systems, orientations, locations, physical settings, plant selection, irrigation systems, and more. Respondents could choose one or more of nine reasons for using a living wall (e.g., It looks nice, It improves air quality, It adds nature into the city, etc.) as well as an additional "other" option.

The performance parameters addressed in the questionnaire were defined by combining the performance parameters used in the previous studies with those identified as offering potential benefits in the literature . The perceived performance was measured by asking the users about the extent to which their living walls were: 'energy efficient', 'water sensitive', 'low in embodied energy', 'biodiversity enhancer', 'urban agriculture facility', 'sense of community enhancer', 'educational', 'relaxing and mood improving', and 'overall successful'. Of these parameters, the last five are considered to be social performance parameters, either wholly or in part. Measuring the performance of the living wall as educational, community enhancer, relaxing and overall successful was done using users' subjective ratings, which is perceived to be the most meaningful way to measure socially related performance (see section 3.2.3).

4.2.2 Closed-ended questions and quantitative analysis

The survey was based on QUT's KeySurvey platform for online questionnaires. The questionnaire was developed and launched using the KeySurvey web interface, and the initial analysis was based on its reporting features. The survey was composed of closed-ended questions, most of them multiple choice. The last question, related to living wall performance, used a five-level Likert scale. Although there's a bias towards the middle values for Likert scale responses, its advantages with speed of response and analysis were considered greater in this study. Building the questionnaire using a closed-ended style was expected to make it easier for the participants to answer the questions (the estimated time requirement was five minutes). This also facilitated straightforward quantitative analysis of the results of the survey.

4.2.3 Approaching existing living wall users

The survey primarily targeted existing living wall users and owners in Israel, particularly in the area of Tel-Aviv. The entire population of living wall users in Israel was sampled by approaching customers of a design firm that supplied living wall products and design services. This purposive sampling method was chosen because it was difficult to identify the population (Blaikie, 2009, p. 178). Only five firms offered living wall solutions in Israel at the time of the survey, and the company chosen was estimated to have an average number of customers and projects. Approximately 80 people were directly approached via email. In addition, around 350 people who identified themselves via the firm's Facebook page (by indicating that they "Like" the page) were potentially exposed to the Facebook invitation, which was eventually viewed by 320 people. It was assumed that people who answered the questionnaire either had an actual living wall or had specific experience with a living wall; otherwise they wouldn't have been able to answer the questions. Therefore, the target audience that actually viewed at least one of the invitations was between 320 and 400 potential participants. A total of 66 respondents voluntarily participated in the survey, equalling a response rate of between 16.5 and 20.6 percent.

Most of the residents of Tel-Aviv are native Hebrew speakers, so the questionnaire was translated into Hebrew and participants could choose whether to answer the English or the Hebrew version at the beginning of the survey. The survey received ethics approval from QUT's Human Research Ethics Committee and met the requirements of the National Statement on Ethical Conduct in Human Research (2007). This process required filing an application including the survey questions, email to participants, Facebook post, and accessibility to survey data. Ethics clearance number 1300000191 was received on May 2, 2013, and the survey was categorised as low risk.

The survey was developed at the beginning of 2013 in order to collect data regarding actual living walls in urban settings in Tel-Aviv and on how the performance of the living walls was perceived by their users. The online questionnaire was launched on May 18, 2013, and it was accompanied by email invitations and a Facebook invitation. A reminder email was sent to the target audience one week later. An additional Facebook invitation was published on May 29, 2013. The survey was open to participation until June 1, 2013, and took approximately 5 minutes to complete.

4.2.4 Analysing survey results

The survey results were entered into a data sheet for analysis that was designed to contribute knowledge in several ways. First, the data related to design parameter values and context parameter values (living wall characteristics) was analysed by identifying clusters of data points. This process detected 'schemes' of living walls. User ratings of reasons for using living walls were then averaged, which allowed a description of generalisations regarding living wall users' incentives. Finally, the participants were sorted according to multiple criteria into two or more groups (e.g., small living walls vs. large living walls) and the ratings of the two groups' various performance parameters were compared. These comparisons revealed the relationship between the living walls' design/context and their performance. The difference between the groups in each comparison was tested for significance using T-test, where p-values of less than 0.05 were considered statistically significant.

4.2.5 Summary of the survey method

The second study was based on a living wall user survey incorporating data from the users' perspective that was based on real-life projects. It included questions regarding the characteristics of the living wall, the reasons for using it, and the performance of the living wall as perceived by its users. The survey consisted of a closed-ended, online questionnaire that was open to volunteer participants from a target audience of living wall users in the Tel-Aviv area. The survey received ethical approval and was available for two weeks. A total of 320 to 400 people viewed the invitations to participate in the survey. The response rate was around 20%, as 66 participants were attracted of that total.

4.3 Building Energy Simulations for Parametric Study

It was previously established that there is a large potential for living walls to conserve building thermal energy (see Table 2.1). However, most of the existing knowledge related to this performance aspect is not connected to design decisions for living walls. To address that gap and describe the relationship between living walls' design and their contribution to building energy efficiency, a set of energy simulations was created. These simulations allowed for a parametric study of the various living wall parameters in two specific climates: Mediterranean Tel-Aviv, Israel, and subtropical Brisbane, Australia. The energy simulation tool was EnergyPlus, developed by the US Department of Energy (Crawley et al., 2001). The following sections review relevant simulation tools that were evaluated (Tas, TRNSYS, and EnergyPlus), explain why the EnergyPlus tool was chosen, describe the tool and its EcoRoof module, and finally, describe the building model created for the study and the procedure that incorporated EnergyPlus for parametric study.

4.3.1 Evaluating energy simulation tools

When planning the building energy simulation study, different practices of thermal simulations of green roofs, as well as relevant simulation tools, were evaluated in order to choose the most suitable tool. To assess the various options for thermal simulation of living walls, related studies that simulate thermal performance of green roofs were found in the literature (Lazzarin, Castellotti, & Busato, 2005; Martens, Bass, & Alcazar, 2008; Sailor, Elley, & Gibson, 2011; Zhao, Tabares-Velasco, Srebric, Komarneni, & Berghage, 2014). Thermal simulation of green roofs was similar to that of living walls, as green roofs' thermal behaviour was influenced by the existence of living plants and their special characteristics. One of living plants' unique attributes is an evapotranspiration process that creates a cooling effect. Unfortunately, evapotranspiration (and evaporation in general) was usually not modelled in thermal performance software beyond some limited modelling of evaporative coolers.

In what was possibly the first thermal simulation of green roofs, Barrio used a simplified representation of green roofs containing three layers: support layer, soil layer, and canopy layer. Since "the complexity of a canopy … is such that an exact description of its physical behaviour is almost impossible" (Barrio, 1998, p. 182), the canopy in this study was represented as a homogenous layer. A simplified approach to modelling green roofs within simulation software is to estimate their R-values and then model the green roof as a standard material with the estimated R-values (Wong et al., 2003). This is a relatively easy approach, but it is not accurate, and it probably underestimates the special attributes of living plants. Indeed, a simulation of green roofs using the TRNSYS building simulation software showed that evapotranspiration is very important, especially during the dry summer months in the Mediterranean climate when the soil is wet (Lazzarin et al., 2005).

Several software tools were evaluated as options to test the thermal performance simulation of living walls while this study was planned. The tools were examined to determine their ability to model living walls' thermal effects, to use weather data for both Brisbane and Tel-Aviv, to model various building designs and details, and to generate energy consumption results.

First Tas (version 9.0.9c), a thermal simulation software for new or existing buildings was evaluated. It allowed users to compare alternative heating/cooling strategies and façade designs on the basis of comfort, equipment sizing, and energy demand. Tas models the 3D building structure (surfaces, windows, etc.) in its 3D Modeller module. It then simulates the different zones, natural and forced airflow, sunshine effect, and internal gains with its Building Simulator module. It then outputs the indoor air temperature for each thermal zone and the heating/cooling load of the building's HVAC systems. The results are viewed in the Result Viewer module (Jones, 1990). Tas was suitable for modelling a specific living wall project, but it could only account for the effects of shading and insulation on the building's thermal performance. Evapotranspiration could be modelled into Tas directly, but it could not be added separately because Tas was a closed software tool with minimal options for customisation. Therefore, a more comprehensive tool was sought.

The TRNSYS modular energy simulation software package was the next to be considered. Developed at the University of Wisconsin (Klein, 2010) to build energy simulations and allow researchers to define different zones in a building, its graphical user interface (TRNSYS Simulation Studio) creates simulations by dragging and dropping TRNSYS components. At the time of the evaluation, however, it could not model the vegetation layer of a living wall (or of a green roof). Developing and programming such a component was well beyond the scope of this research, given that alternatives with components that did simulate vegetation layers were available for use. Therefore, the software tool that was found most suitable for this research was EnergyPlus.

4.3.2 The EnergyPlus simulation tool

EnergyPlus is a powerful energy analysis and thermal simulation software developed for the United States Department of Energy (DOE) and based on two older software tools, DOE-2 and BLAST (Crawley et al., 2001). EnergyPlus models a building's heating, cooling, lighting, ventilation (among other energy flows), and water. It has no user interface (the input and output are text files), but several available interfaces can be used with it.

In the second version of EnergyPlus (V2.0.0), the EcoRoof model that was added supplies energy consumption estimates for green roof simulations. A computational model of the heat transfer processes relevant to green roofs was developed (DOE, 2010) that accounts for heat and radiation exchange within vegetation and other layers, heat conduction and storage in the soil layer, and evapotranspiration from the soil and plants. EnergyPlus thus allows the user to specify EcoRoof as the outer layer of a rooftop construction and to specify various aspects of the green roof: growing media depth, thermal properties, plant canopy density, plant height, stomatal conductance (ability to transpire moisture), and soil moisture conditions (including irrigation). The green roof module of EnergyPlus was validated against actual observations of a monitored green roof with live vegetation (Sailor, 2008).

The EcoRoof component of EnergyPlus can be modified to model living walls, as EnergyPlus allows software developers to develop and modify modules to complement the simulation engine. This high-end simulation tool and its comprehensive green roof module offered the potential to achieve maximum accuracy with living wall thermal simulation. EnergyPlus, with adequate modifications, was the only tool that allowed both full modelling of vegetation thermal effects (including evapotranspiration) and enough flexibility to model living walls. The main disadvantage of EnergyPlus was that it was relatively difficult to operate. It had no built-in visual interface and only manual editing options that were based on a relatively old programming language. Code changes to EnergyPlus were thus quite challenging.

In this study, the simulations included green roof surfaces that were both horizontal and vertical in order to simulate both green roofs and living walls. The built-in green roof module was used as a basis for building vertical vegetation layers, with their associated growing media layers and other characteristics that were similar for both green roofs and living walls.

4.3.3 Modelling a simple building in Tel-Aviv and Brisbane

The first step was to create a simple model of a building consisting of a single story, a rectangular area with two double-pane windows, a roof, and light walls made of layers of wood, fibreglass, and plasterboard—materials that are commonly used in residential buildings in Brisbane. The air system assumed infinite cooling/heating regimes. The vertical vegetation model was schematic and consisted of a layer of growing medium and a layer of vegetation. It was assumed that vegetation characteristics were constant year round and uniform across all surfaces. In various simulations, the vegetation covered the entire roof and four walls excluding the windows, as shown in Figure 4.10.

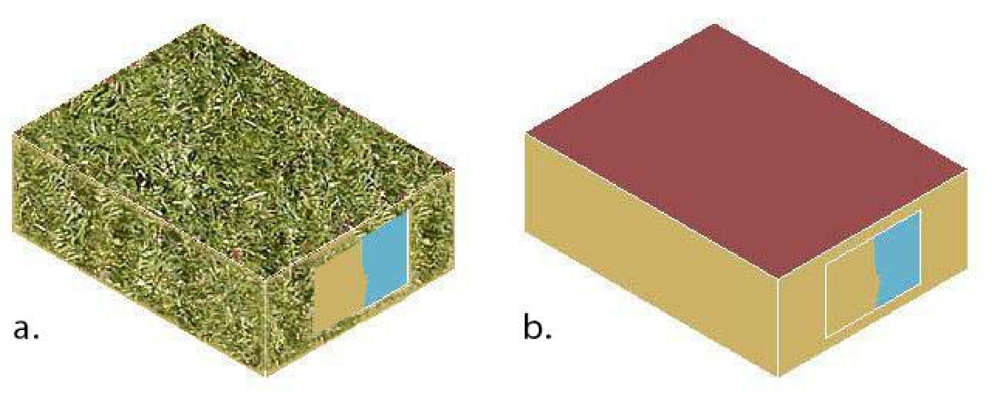

Figure 4.9: Schematic building (a) with maximal vegetation coverage on roof and walls, excluding the window, and (b) without vegetation.

Each simulation measured the amount of heating and cooling energy required over the span of a year using a different set of parameter values. Yearly energy consumption for each simulation was then compared to the control scenario of an exposed building with no vegetation cover in order to estimate the living walls' impact on energy consumption. In comparison to the two prior studies, it was straightforward to incorporate more than one geographic area. Simulations were performed separately for climates in both Tel-Aviv and Brisbane to demonstrate that the method was expandable and that it worked in various contexts.

4.3.4 Parametric study of the relationship between living wall design and building energy consumption

To study how changes in parameter values impacted building energy consumption, it was necessary to change values for each parameter separately while keeping the other parameters' values constant. Therefore, a set of baseline values was defined for the parameters, wherein each received a mid-range value. This set of values was referred to as the *baseline scenario*. For each of the studied parameters, then, energy simulations were performed with all parameter values set to the baseline scenario values except for the targeted parameter that received a range of values.

The list of parameters and their values appears in Table 4.1. For each parameter, the table lists the baseline scenario value, as well as the minimum and maximum values that were used during the simulations. The names of the parameters in the table were taken from the EnergyPlus software. The following are the principal parameters relevant to living wall design:

Height of Plants: The estimated height (or rather, the length of the plant stems) for living wall vegetation was between 10 and 50 centimetres. Mature plants are rarely shorter than 10 centimetres, while very tall plants tend to break or bend upward as they mature in a vertical setting, so the maximum plant height cannot exceed 50 centimetres. Therefore the baseline value was set to 30 centimetres (0.3 m).

Leaf Area Index (LAI): In various green roof studies, the LAI was assumed to be around 3—a typical number for green roofs with grass (Currie, 2008) and for ivy cover (Takakura, Kitade, & Goto, 2000). This was chosen as the baseline value for the LAI of plants in this study.

Thickness of Growing Substrate: Green roofs usually have growing substrate thicknesses of around 15 centimetres, though that figure can be as high as 30 centimetres for intensive green roofs. However, living walls may have no growing substrate at all (in the case of green façades) and typically had a slimmer substrate of between 5 and 10 centimetres. To balance those factors, the baseline value chosen was 8 centimetres.

Weather Files: The two climates tested were the Tel-Aviv and Brisbane climates. Both are hot climates with maximal daily temperature of more than 24Cº for 7 months per year in Tel-Aviv (Israeli Meteorological Service, 2013) and for 8 months per year in Brisbane (Bureau of Meteorology, 2013). Both areas require building cooling to ensure their occupants' thermal comfort. The weather files include hourly data for air and ground temperatures, wind, humidity, solar radiation, and so on. The following weather files were used:

- Yearly Tel-Aviv weather data that was developed in 2010 by the Faculty of Civil and Environmental Engineering at the Israel Institute of Technology (Technion) in Haifa.
- Yearly Brisbane weather data that was created in 2006 based on data from 1967–2004.

Irrigation was set for two hours each morning. The irrigation rate (in cm per hour) uses two different values, with the irrigation rate for summer higher than the irrigation rate for winter months in both climates. Note that the irrigation parameter in this simulation has an impact only on the amount of moisture available for evapotranspiration. The simulation could not guarantee that the timing and amount were optimal for the plants.

Living Wall Aspects: The simulations were performed separately for each wall coverage aspect: north wall, south wall, west wall, and east wall, and various combinations of those.

Table 4.1: Living wall parameters studied in the building energy simulation. Baseline, minimum, and maximum values presented per parameter.

	Parameter Name (EnergyPlus)	Baseline Value	Min.	Max.	Comments
Vegetation	Height of Plants [m]	0.3	0.01	1	0.1–0.5 reasonable for living walls
	Leaf Area Index	3.0	0.001	5	
	Leaf Reflectivity	0.22	0.1	0.4	Typically 0.18–0.25
	Leaf Emissivity	0.95	0.8	1	Default=0.95
	Minimum Stomatal Resistance [s/m]	180	50	300	
Growing Substrate	Roughness	Medium Smooth			6 values: VerySmooth to VeryRough
	Thickness [m]	0.08	0.05	0.5	0.15 & 0.30 common for green roofs. Living walls are slimmer
	Conductivity of Dry Soil [W/m-K]	0.4	0.2	1	Typically 0.3–0.5 for green roof substrate (Sailor, 2008)
	Density of Dry Soil [kg/m3]	641	300	2000	Typically 400–1000
	Specific Heat of Dry Soil [J/kg-K]	1100	501	2000	Typically 800–1600 (Sailor, 2008)
	Thermal Absorptance	0.95	0.81	1	Typically 0.90–0.98
	Solar Absorptance	0.8	0.4	0.9	Typically 0.6–0.85
	Visible Absorptance	0.7	0.51	1	
Moisture in Growing Substrate	Saturation Volumetric Moisture Content of Soil Layer	0.4	0.11	1	Typically less than 0.5
	Residual Volumetric Moisture Content of Soil Layer	0.01	0.01	0.1	
	Initial Volumetric Moisture Content of Soil Layer	0.2	0.11	1	
	Irrigation Daily Rate [cm/hr]	0.2, 0.1	0	0.3	Rates for summer and winter, set for 2 hours every morning
HVAC Thermo-stat	Thermostat Set-Points [ºC]	20–24			Studied 19–25ºC and 21–23ºC
	Thermostat Schedule	Always			Daily schedule 8:00–18:00
Living Wall Aspects	Living Wall Geometry	All aspects			North, South, East, West, and combinations
Climate	Weather File	N/A			Tel-Aviv and Brisbane

For each of the parameters, a group of simulations were performed with values of all parameters set to those defined in the baseline scenario and the results were recorded. The studied parameter was set to its minimum value and the result was recorded. It was then increased to the next value while keeping all other parameters values constant, and the result was recorded. More simulations were performed in a similar manner, increasing the value of the studied parameter incrementally and recording the results each time. Eventually the studied parameter reached its maximal value and this was the last simulation in that group.

For example, when studying the growing substrate thickness parameter, the first simulation was performed with all parameters set to their baseline values, and the thickness was set to 0.06 (6 cm). The resulting cooling energy value over a year was 4266.5 kJ. In the next simulation, only the substrate thickness value was changed to 0.08 and the result was 3815.1 kJ. The values of the substrate thickness parameter were increased before each simulation until, in the fifth rendition, it reached the maximal value for this parameter—0.14. The results for the final simulation were 3059.2 kJ.

An exemplar of the complete set of results from changing the growing substrate thickness parameter in the Tel-Aviv climate is depicted in Table 4.2. In this table, the results obtained for each value were also converted to a percentage of energy saved when the cooling energy required when the building was covered by an ever-increasing substrate layer was compared to the cooling energy required for the building with no vegetation cover.

Table 4.2: Example of parametric analysis of substrate thickness of living walls in the Tel-Aviv climate and its influence on energy consumption and savings

Substrate Thickness [m]	Yearly Cooling Energy [kJ]	Yearly Energy Savings
0.06	4266.5	20.3%
0.08	3815.1	28.8%
0.10	3486.6	34.9%
0.12	3225.7	39.8%
0.14	3059.2	42.9%

The above procedure was repeated for each of the 20 studied parameters, producing a set of 20 groups of results—one for each parameter. The entire procedure was actually repeated twice, once for each weather file (Tel-Aviv and Brisbane). The study thus included a total of approximately 200 simulations.

4.3.5 Sensitivity analysis of parameter values

A sensitivity ranking (as described by Hamby, 1994) results in an ordered list of parameters, sorted according to the extent to which they influence the results. The sensitivity is calculated using the *direct method*, which is also referred to as *differential sensitivity analysis*. This method can be applied either numerically or symbolically.

The numerical method calculates an approximation of the differential value of a point by dividing the difference in output between two points by the difference in input between those points, whereas the symbolical calculates the derivative function of the output function of the system. In both cases a derivative function can be plotted. In instances where the derivative function is 0, the system function does not change as a result of changing inputs. However, where the derivate function value is high, the output function changes a great deal in response to very slight changes in the input. Additionally, in places where the derivative function value is low, the output function changes only slightly in response to large changes in the input. And so, in this way, the derivative function is an accurate descriptor of the sensitivity of the output to the input, as we intuitively understand the term.

The direct method is used because it "is the backbone of nearly all other sensitivity analysis techniques" (Hamby, 1994). More importantly, the results of this method of analysis on this system give a sufficiently clear picture of the influence the input has on the output.

The parameter values (input) were taken at regular intervals, despite the fact that randomised parameter values are normally used (i.e., in instances where complex systems are relatively unknown and for which no previous mathematical characterisation has been made). In this study, two factors justify the use of uniform as opposed to random sampling of the input: the output function is not periodic, and the output function is continuous and differentiable.

The goal of the sensitivity analysis was to understand how variations in each of the living wall parameter values impacted building energy consumption. In order to achieve this, the results of the simulations were comparatively analysed. For each parameter, the results of the corresponding group of simulations were used to generate a plot of energy consumption values versus parameter values. These plots were then subjected to sensitivity analysis so that cases where parameter-value increases were correlated with increased energy savings (or vice versa) could be recognised. Special attention was paid to non-linear graphs and to parameter values that corresponded to peaks or curves in the graphs.

For example, when studying the influence of LAI on cooling energy savings in Brisbane, it was found that increasing LAI resulted in lower cooling energy consumption. The effect of changes in LAI were dramatic but, surprisingly, when the LAI rose above 4, the resulting energy savings were negligible. This means that LAI=4 produced the optimal result possible in terms of building cooling energy savings, as presented in Figure 4.11.

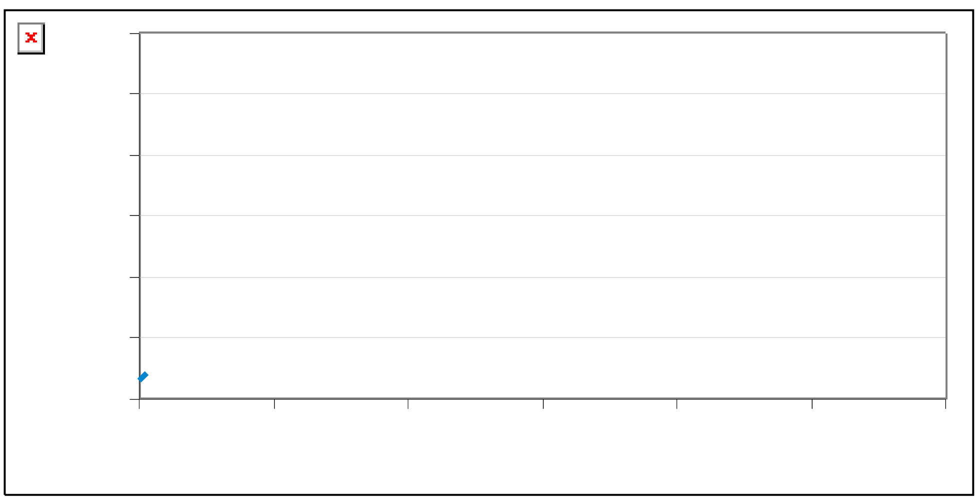

Figure 4.10: Increasing LAI of vegetation increases cooling energy savings in the Brisbane weather simulations. The greatest savings were achieved when LAI reaches 4 or more.

4.3.6 Summary of the simulation method

In order to design the living wall parametric study using building energy simulations, simulation studies of green roofs were reviewed. Existing simulation software tools were then assessed and EnergyPlus was chosen owing largely to its EcoRoof module that simulates live vegetation layer behaviour. The study was based on a model of a simple building that was built into the EnergyPlus software. More than 200 energy simulations were then executed, with each simulation testing different parameter value combinations. In this study, the context was extended to include the Brisbane climate in addition to Tel-Aviv's as a way to demonstrate the method's scalability. Sensitivity analysis of the simulation outputs was conducted to identify patterns in the relationships between living wall parameter values and building energy consumption levels. The results of the simulations inform our knowledge of the relationship between living wall design parameters and building thermal energy consumption.

4.4 Summary of Methods

The three studies in this research used different methods to reveal relationships between a living wall's design and its expected performance. The design parameters and the performance parameters involved in the three studies varied in the following ways:

- To study levels of food production, the design parameters were related to the characteristics of each of the six living wall systems used and to the irrigation schedule and plant selection. The context remained the same for all systems tested and was set by the study location—a domestic backyard in a residential neighbourhood in Tel-Aviv. The performance parameters were the living wall systems' productivity, user experience, water efficiency, and embodied energy.
- The design and context parameters in the user survey study were the characteristics of the living wall project, including the system used, the dimensions, the location, and the social context. The performance parameters were nine aspects of the living wall's performance (as perceived by users).

- The building energy simulation study's parameters were based on the EnergyPlus simulation tool's available parameters (principally plant characteristics and the living walls' physical properties). The study was performed for the climates of both Tel-Aviv and Brisbane. The performance parameter was the building's cooling energy consumption.

Table 4.3 summarises the design and context parameters used in each of the three studies and the performance parameters measured. The next chapters present and analyse the results of the three studies.

Table 4.3: Living wall parameters and performance parameters addressed in each of the three studies

Study	Design & Context Parameters	Performance Parameters
Edible Living Wall Case Study	Design parameters of living wall systems, plant selection, and irrigation. Tel-Aviv location	Food production, user experience, water efficiency, and embodied energy
Living Wall User Survey	Design parameters such as system, dimensions, plant selection and irrigation. Context parameters such as settings, area and users. Tel-Aviv location	Perceived performance in terms of overall success, energy efficiency, water efficiency, embodied energy, biodiversity enhancement, productivity, education, psychological benefits, and community values
Building Energy Simulation	Living wall orientation, substrate properties, vegetation properties, moisture in substrate, and weather (Tel-Aviv/Brisbane)	Building thermal energy savings

5 Edible Living Wall Case Study Results

In the edible living wall case study, six different living wall systems were used to grow edible plants in a domestic setting. All edible plants chosen were species that can be grown successfully in the Tel Aviv area using standard soil-based vegetable beds. Each system represented a specific case characterised by a set of design parameter values (e.g., materials, dimensions, planting angle, etc.). This study was intended to address the first research question by:

- describing the six cases of living wall systems and their characteristics;
- supplying data on the extent to which these edible living wall cases were able to produce food; and
- parametrically studying the changes in living wall parameter values between the systems and how those changes relate to food production and other performance parameters.

Section 5.1 describes each of the cases and each system's overall results. The next sections (5.2–5.5) delineate comparisons between the living wall systems according to the four performance parameters (food production, water efficiency, embodied energy, and user experience), analysing the relations between the systems' design parameter values and their performance. Section 5.6 offers additional observations related to design parameters.

5.1 Six Living Wall Systems for Food Production

This section describes each of the living wall systems' overall performance. It provides details pertaining to the following selected (see section 4.2.5) performance parameters:

- food production–harvest description and total weight;
- water efficiency–irrigation scheme and daily watering schedule;
- user experience–issues such as setup difficulty, ease of maintenance,

and appearance; and

- embodied energy–materials, manufacturing, and end of life.

5.1.1 The Woolly Pocket case

The Woolly Pocket system covered a vertical area of 1.92 square metres, and the total harvest from the plants growing in it over the entire year was 5,260 grams. It produced a markedly large yield of herbs, leaf vegetables, and brassicas (3 cabbage heads weighing a total of 1.8 kg), though legumes, fruit vegetables, and other brassicas did not mature. Only 1 or 2 eggplant fruits developed per plant during the summer season; kohlrabi reached a diameter of 4 centimetres; and legumes did not produce any harvest at all. Of the root vegetables, the only harvest was 2 radishes weighing 10 grams in total. A Micro-Tom variety of tomatoes, however, successfully yielded around 20 cherry-sized tomatoes per season.

In the case of the Woolly Pocket system, the available root space per plant was 3.8 litres on average. The maximal root space per plant was 33.9 litres, but the shared root space was arranged sideways so roots could utilise the extra space next to them only by growing horizontally, which they were less prone to do than growing vertically or growing both vertically and horizontally. Growing horizontal roots is more natural in some plant species than in others. For example, mint grew roots and runners sideways, so it utilised the horizontally interconnected root volume effectively. Spring onion (also known as bunching onion) formed bunches of stems in the Woolly Pocket system compared to the relatively narrow form this vegetable took in the Domino Planter system.

The Woolly Pockets required two four-minute-long watering sessions per day in the summer. The Woolly Pocket watering amount and frequency was identical to the Invivo Pocket's watering characteristics, although there were more emitters per volume of growing substrate in the Woolly Pockets. This was probably because the Woolly Pocket system had a moisture barrier only at the back. The front and bottom were free to drain and to evaporate moisture, thus losing some of the water. The Woolly Pocket system's irrigation layout is shown in Figure 5.1.

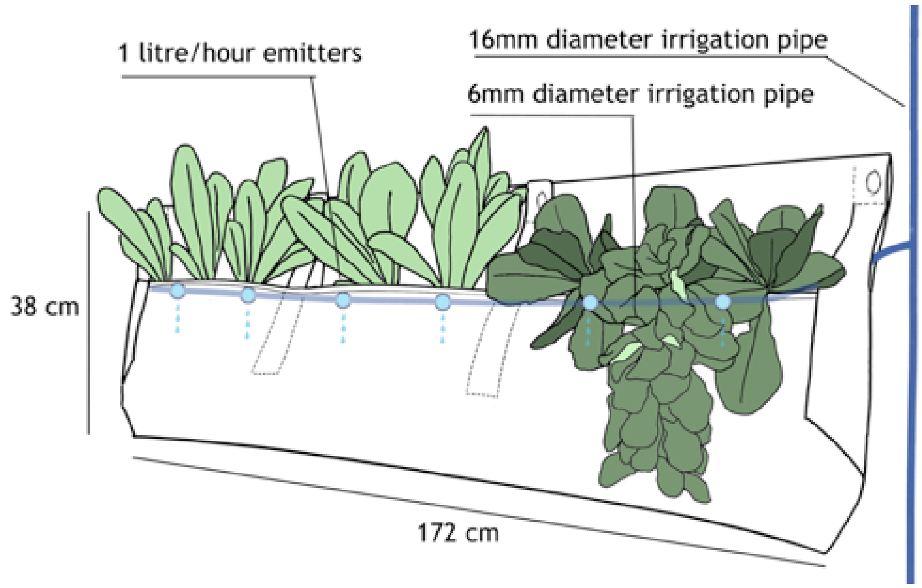

Figure 5.1: Irrigation layout for the Woolly Pocket system

The Woolly Pocket system was manufactured in the U.S., mainly from synthetic felt made from recycled PET bottles. Using recycled material requires more energy than reused material, but this is still a good option for lowering a system's amount of embodied energy. Another layer of the product, the moisture barrier, is made out of polyurethane (details regarding where the polyurethane was manufactured were not available). The fact that neither source materials nor manufacturing were near the study location made this alternative an even less efficient option; However, American living wall installations will incur a lower level of embodied energy, and what was a disadvantage for this study's location will be advantageous in the U.S. The manufacturer claims that Woolly Pocket products include UV protection and that their expected lifespan is 15 to 20 years. The manufacturer also claimed that the product is 100 percent recyclable, although the layers of PET and polyurethane must be separated to recycle them, and no details were provided regarding any recommended procedure to isolate the different source materials.

5.1.2 The Aria case

The Aria system covered a vertical area of 2.04 square metres and produced a harvest of 15,110 grams over the entire year. Nearly all types of vegetables and herbs were successfully grown in the Aria system. Tomatoes and legumes yielded considerable amounts, probably due to their ability to "climb" and be propped up by the supporting structure or by surrounding plants. On the other hand, only one small (200 gr) eggplant fruit was harvested, and no zucchinis were harvested at all. This is probably due to insufficient light. If so, this could be corrected by factoring in different light conditions. Root vegetables were difficult to germinate due to the planting angle, and none were harvested.

Each plant in the Aria system had an average of 3 litres of substrate root volume. However, since all the panel cells were interconnected, the plants could utilise up to 24 litres on average. Plants at the top had 36 litres available to them, while the lowest plants had only the bottom row available (i.e., 12 litres of substrate volume).

The irrigation schedule for the Aria system (Figure 5.2) was twice daily for 4 minutes, identical to the schedule of both the Invivo Pocket and the Woolly Pocket systems. However, the Aria system used 12 emitters per 36 litres of substrate (one emitter for every 3 litres, on average), whereas the Invivo Pocket used one emitter for every 8 litres of substrate. The Aria system was thus less efficient than the Invivo Pocket, probably because the relatively large surface area allowed moisture to evaporate, and the containers' slanted-bottom design increased the amount of drainage.

The Aria system was manufactured in the U.S. from new, high density polyethylene (HDPE). Its manufacturing process was highly professional, and it entailed steep energy costs. Importing this relatively large system from the U.S. to Israel also meant it left a significant environmental footprint. According to the manufacturer, the Aria system included UV protection and its expected lifespan was 15 years. The recycling of HDPE is both possible and straightforward, and the Aria system was therefore considered 100% recyclable.

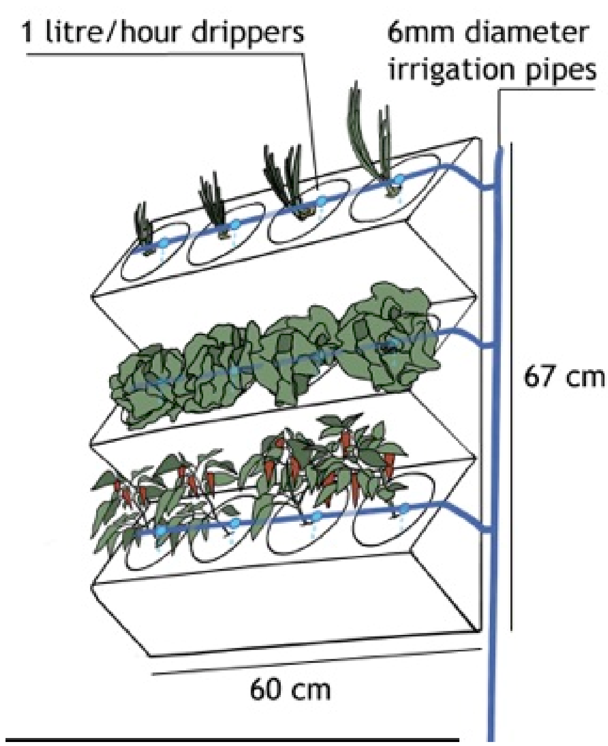

Figure 5.2: Irrigation layout for the Aria System: One emitter per slot.

5.1.3 The Domino Planter case

The Domino Planter system covered a vertical area of 1.8 square metres and produced a harvest of 1,020 grams over 6 months. Most of the leaf vegetables and herbs did not grow very large in the Domino system. Lettuce and rocket were grown and harvested, but the system cannot be considered an effective way to grow these vegetables (Only 140 gr of rocket and 800 gr of lettuce leaves were harvested.). Of the herbs planted, only the mint and parsley reached a yield-producing size.

The root space available for each plant in the Domino system was approximately 1.6 litres on average, with a maximal volume of 9.4 litres for plants that utilise the entire volume of the panel. Figure 5.3 shows lettuce that grows with very limited root space in the Domino Planter system. The top row illustrates larger heads, probably owing to the roots' tendency to grow downwards and use the space below. Mint utilised root space from left and right, and was even found to use root volume available at a higher elevation than where it was originally planted.

Figure 5.3: Lettuce growing in limited root space inside the Domino Planter

In terms of irrigation, each Domino Planter had a line with three emitters at the top (Figure 5.4), so that each emitter could water the two plants below it. The Domino Planters were watered twice daily for 3:30 minutes each time.

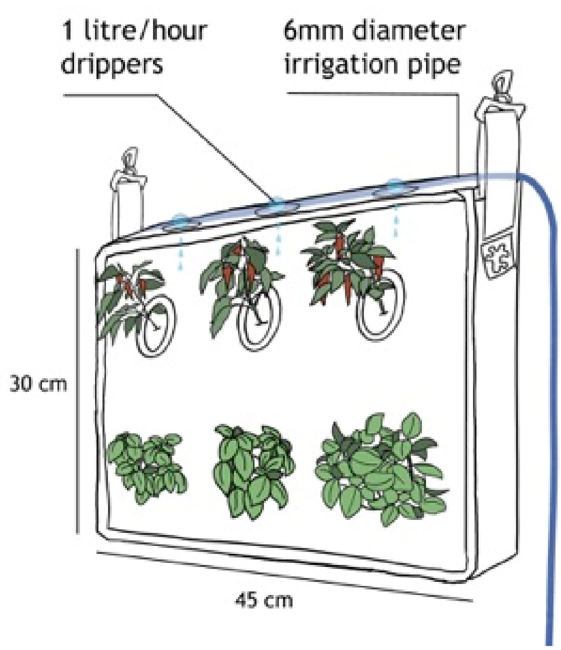

Figure 5.4: Domino Planter system irrigation layout with three emitters at the top

The Domino Planters were cut and sewn in Australia from new PE sheets. However, they required a special substrate of Fytocell foam to be used. For this study, the Fytocell was imported from the Netherlands. It was foamed and cut in the Netherlands, shipped to Israel, and then inserted into the flexible planters that were shipped from Australia.

The Domino Planters were made of UV protected PE sheets that carry a 3-year manufacturers' warranty but they were expected to have a life expectancy of 6 years in Israel's climate. The PE sheets, which were the main source material of the Domino Planters, are fully recyclable so the entire product was considered 95% recyclable.

5.1.4 The ELT case

The ELT system covered a vertical area of 1.2 square metres and produced 740 grams of harvest during five months. None of the plants in any of the categories reached maturity. However, leaf vegetables are edible from the earliest stages so they could be eaten even though the ELT system's geometry arrested their development. Because it was not possible to sow seeds in the ELT system and because root vegetables are harmed if they are transplanted at early stages of their development, root vegetables could not be grown in it at all. Overall, the total yield of vegetables in the ELT system was small when compared to the other systems. After May 2012, when the winter crops were all harvested, the ELT system was planted with ornamentals.

The ELT system's inadequate food production levels may have been attributable to the very limited root space per plant. The available root space per plant in the ELT system was limited to only 0.95 litres per plant on average. Although some plants managed to grow roots through the drainage openings downward to adjacent cells, most of the root volume was confined to the cell where the plant was planted. When observing the roots of plants that were taken out of the ELT panel, it was apparent that the substrate space was filled with roots (Figure 5.5) indicating that root volume was the factor that limited the growth of vegetables.

Root volume limitations influenced the size of the leaf vegetables as can be seen in Figure 5.6, which shows lettuce leaves shorter than 10 centimetres growing in the ELT system.

Figure 5.6: Lettuce varieties grew in less than 1 litre of root volume available in the ELT system

Figure 5.5: Lettuce and celery roots filled the available root space in the ELT system

The ELT system required frequent watering (3 times a day) since so much of its growing substrate surface was exposed to the air that it had a larger rate of evaporation. On the other hand, only two emitters per panel were needed to support up to 10 plants (see Figure 5.7). This is more efficient when compared to the other systems, probably because the flow of water inside the panel from top to bottom was assisted by the design of the diagonal slats. See Figure 5.7 showing the irrigation layout in the ELT panels.

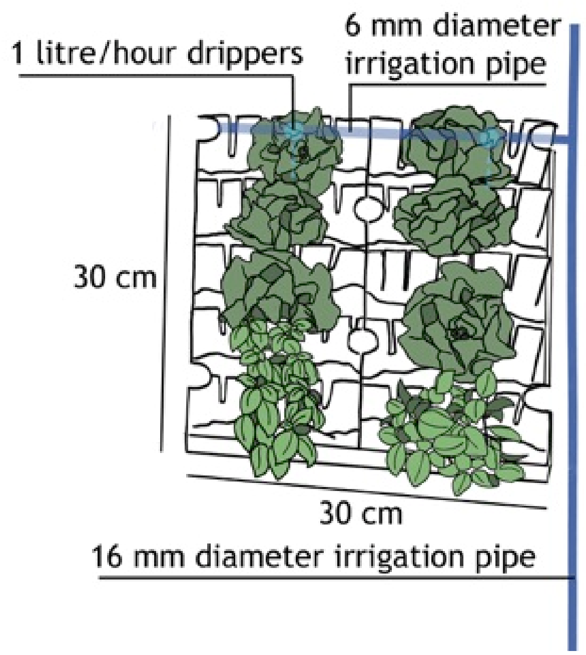

Figure 5.7: Irrigation in the ELT system:
Emitters are placed at the top of each panel

Using the ELT system uncovered a parameter that had not originally been considered: the stability of the growth substrate. In several scenarios—including when planting seedlings, replacing plants, and sometimes even when watering—the substrate inside the ELT system tended to spill out. This was a result of the geometry of the plastic containers holding the substrate and because they were not designed as a living wall for seasonal plants. In fact, the ELT panels were supposed to be planted horizontally and then hung vertically a few weeks later, once the plants' root systems were established.

The ELT system was manufactured in India from new high density polyethylene (HDPE). Its manufacturing process was highly professional and consumed a significant amount of energy. Similar to the Aria system, the ELT system was relatively large in volume and therefore the environmental load of transporting it from India to Israel was high. The ELT system's manufacturer claimed that it was UV protected and that its expected lifespan was 15 years. The recycling of HDPE is possible and straightforward, and the ELT system was therefore considered 100% recyclable.

5.1.5 The Invivo Pocket case

The Invivo Triple Pocket system covered a vertical area of 3.6 square metres and produced a harvest of 20,280 grams over the entire year. All types of vegetables were grown in the Invivo Pocket system, with mostly good results. The horizontal planting angle in the pockets made it possible to sow directly in the pockets, allowing for easy root vegetable growing (e.g., radishes, medium-sized carrots, and beetroots—see carrots in Figure 5.8). The Invivo Pocket system's versatility facilitated an acceptable growth rate and level of productivity for legumes and fruit vegetables and an even greater productivity level for herbs and leaf vegetables.

In terms of available root space, each pocket contained 8 litres of growing substrate, but the roots were confined to the space in the pocket and could not expand into adjacent pockets. Figure 5.9 shows lettuces that are around 15 centimetres high, which is considered full size for this type of lettuce (green and red butterhead). Study results also indicated that two lettuce heads could be grown in each 8-litre pocket without compromising their size at maturity.

The Invivo Pockets were watered twice a day from one emitter in the middle of each pocket. This watering regime sufficed even when a single Invivo pocket held more than one plant. The moisture was able to spread inside the pocket and was then retained by the material's moisture retention properties. See figure 5.10 for the irrigation layout of the Invivo Pocket system.

Figure 5.9: Lettuce growing in one of the pockets forming 15-cm high lettuce heads

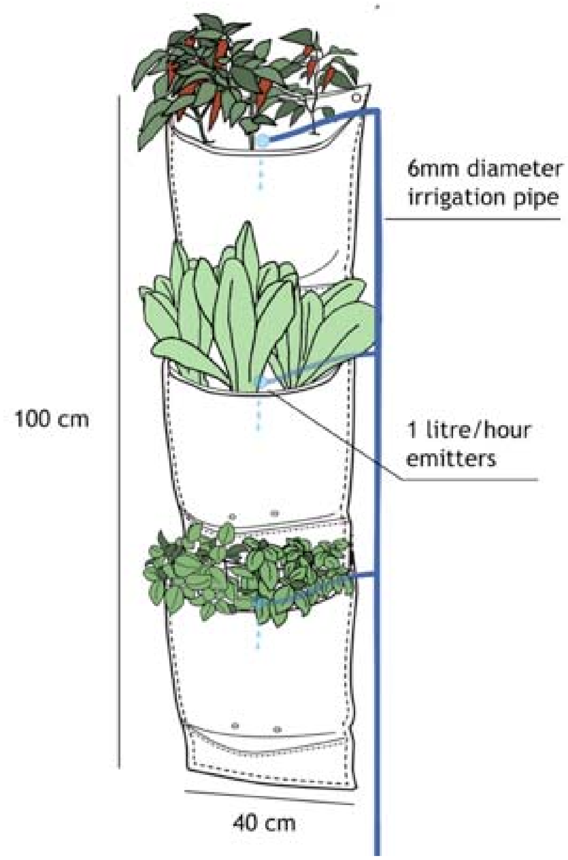

Figure 5.10: Invivo Triple Pocket irrigation layout with one emitter per pouch

The Invivo Pocket system was constructed largely of reclaimed billboards that were retrieved, cleaned, cut, and sewn. The additional materials (eyelets and synthetic tape) are insignificant in terms of their relative mass and embodied energy. The sewing stage required skilled work and professional equipment (mainly sewing machines), but almost all materials were reused and sourced locally. Manufacturing was thus locally based and consumed little energy. Both the Reclaimed Pallets and the Invivo Pocket systems were developed during this study in order to create an alternative involving local manufacturing and reusing source materials. The Invivo Pockets were made of UV protected plastic sheets (PVC/PE) and UV protected threads. Their manufacturers' warranty was only three years, but a life expectancy of six years was expected in climates like Israel’s. The Invivo Pockets were manufactured from PVC/PE sheets that are not easily recyclable because of the combination of raw materials. They would inevitably end their life in the landfill.

5.1.6 The Reclaimed Pallet case

The Reclaimed Pallet system covered a vertical area of 1.2 square metres and produced 8,760 grams of harvest during the entire year. Most types of vegetables were successfully grown in the Reclaimed Pallet system. Root vegetables could not be sown directly in the pallet due to its planting angle. Some of the brassicas reached mature size (kale with leaves 40–50 cm long), but the cauliflower did not flower and the cabbage did not form heads. Note that the top of the pallet was found suitable for tall plants such as maize because it allowed a horizontal planting angle and offered deep root space (see section 5.1.7 regarding root space). The bottom of the Reclaimed Pallet system was especially suitable for zucchini, melon, watermelon, and pumpkin, due to the cucurbits' ability to spread and get support from the nearby ground area. In that sense, it is notable that using the special characteristics of the border areas of the vertical system (the top and the bottom) can vary the growing conditions and thus expand the repertoire of vegetables that can be grown in this living wall system.

When compared to the others, the Reclaimed Pallet system was best suited for growing fruit vegetables (mainly tomatoes, cherry tomatoes, zucchinis, and other cucurbits). This was probably because these vegetables require significant root volume to achieve high productivity, and the pallet system had the most volume of those tested. This was also the only system where maize was grown: When planted at the top, the available root volume was very deep and the planting orientation was horizontal. However, the top area was relatively small, and only a couple of cobs were harvested, making this insignificant in terms of total yield.

In terms of available root volume, the pallet system supplied each plant with an average of 12.5 litres of growing substrate. Since the growing substrate was only divided into three separate sections, up to 40 litres of growing substrate could be available per plant. Since roots grew mostly downwards (positive gravitropism), the top plants had the most potential volume for their roots, whereas bottom plants could not exploit the large shared space. This may be why the maize could reach a mature size when planted at the top of the pallet system.

The Reclaimed Pallet system's irrigation layout was simple: Only six emitters were mounted at the top of the pallet (Figure 5.11). The water trickled down the growing substrate by gravitation alone. The Reclaimed Pallet system had a relatively long irrigation period per day (9 minutes), but since it only had six emitters per pallet, it was actually the most water-efficient system, as presented in section 5.3.

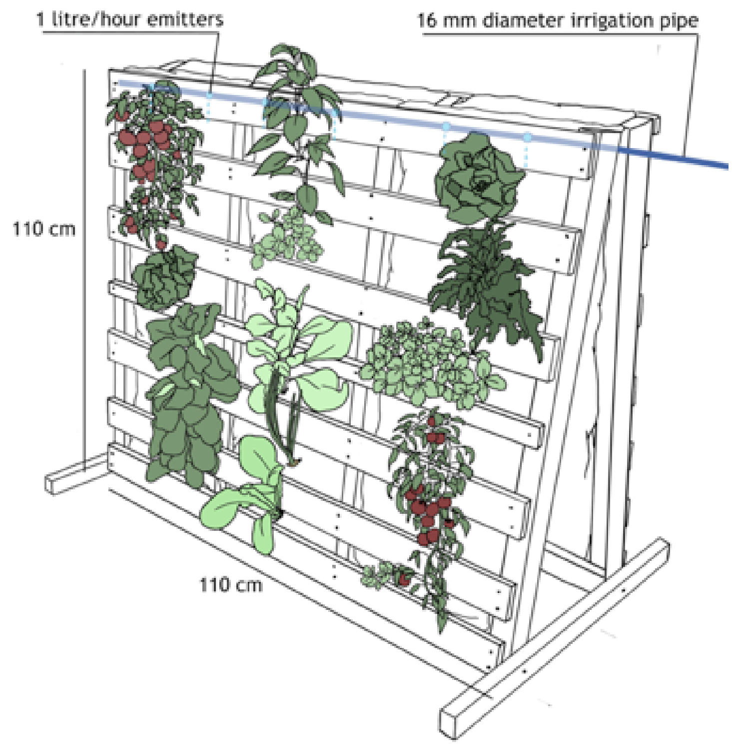

Figure 5.11: Reclaimed Pallet irrigation layout with emitters only at the top

The Reclaimed Pallet system (see Figure 5.12) was constructed mainly from used pallets retrieved from the street and used flour bags retrieved from a local grocery store. The few nails and screws required used insignificant amounts of energy, and assembling the system took relatively little time or energy. This makes it this study’s most energy efficient living wall system with respect to manufacturing requirements. The Reclaimed Pallet system’s flour bags were not UV resistant however, and by the end of the study, the bags showed signs of deterioration approximately one year of use, so they would need to be replaced every year or two. The pallets were made of untreated wood that is expected to slowly decompose. The Reclaimed Pallet system's life expectancy was therefore estimated to be not more than three years.

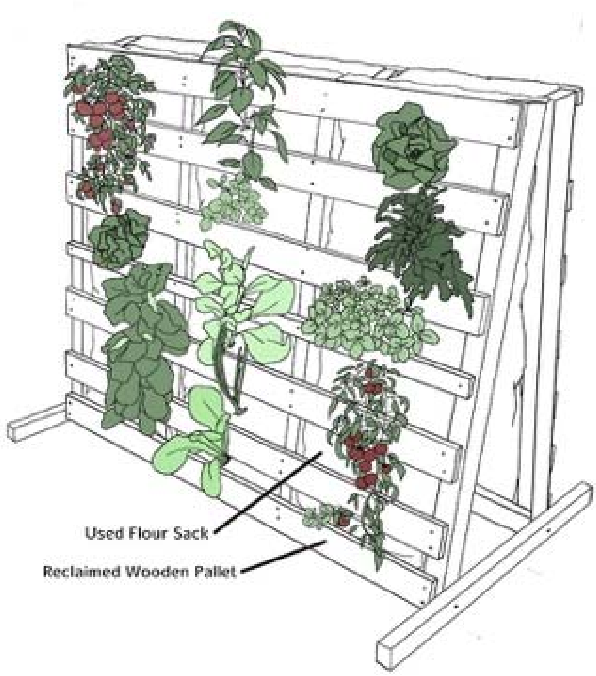

Figure 5.12: Reclaimed Pallet system materials

5.2 Comparing the Food Production of Living Wall Systems

The harvest type and weight of each producing living wall system were documented in the harvest log (see Appendix C). This data was presented per system in the previous section, and was parametrically studied to induce generalisations. The design parameters related to the harvest amounts were available root volume, plant selection, and planting angle. These parameters were used in the parametric analysis of harvest results and the relations between them and the harvest amount are presented here.

5.2.1 Comparing systems' total harvested material

The total harvest weight per system was summarised and controlled according to the number of months the system was active (e.g., ELT and Domino Planters were used for food production only until May of 2012, and the Reclaimed Pallet system was not even built until April of 2012). The results are represented in the bar chart depicted in Figure 5.13. The Invivo Pocket system yielded the largest amount of harvest per month

(1690 gr), followed by the Aria system (1259 gr), the Reclaimed Pallet system (1095 gr), and the Woolly Pocket system (445 gr). The Domino and ELT systems yielded the smallest harvest amounts per month (170 gr and 123 gr respectively).

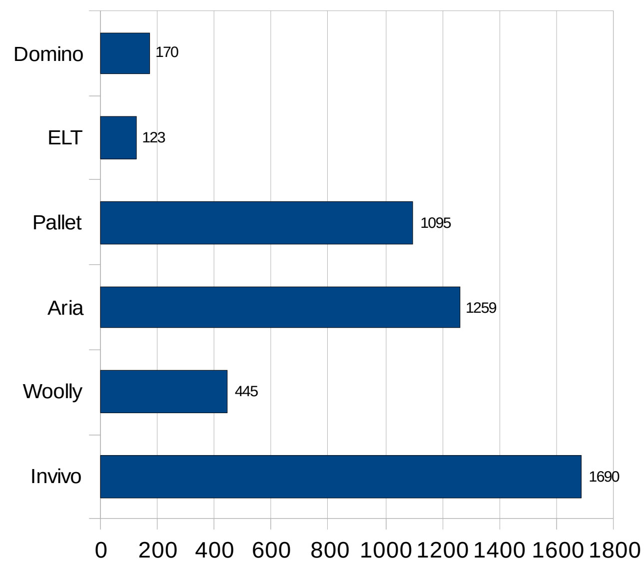

Figure 5.13: Total harvest weight in grams per month for each system

It was not surprising that the Invivo Pockets yielded the largest amount of harvest since they covered a 3.6-square-metre area of fencing, larger than the area covered by the other systems (1–2m^2). Therefore, the results also controlled for the vertical area covered by each system. The resulting metric—harvest weight per month per square metre—was calculated for each system and is presented in Figure 5.14.

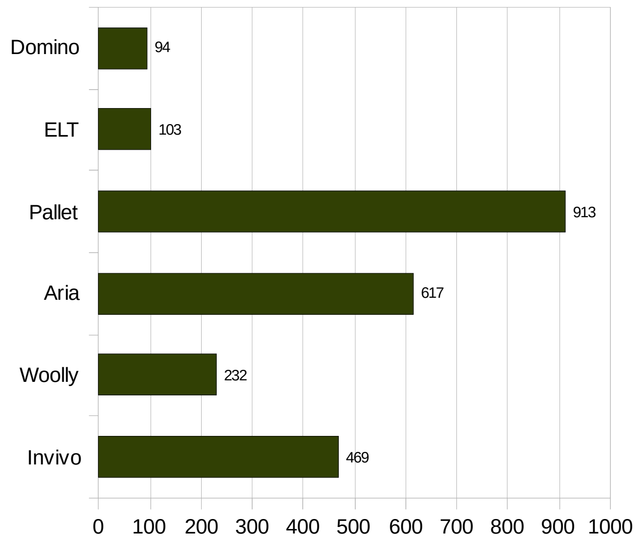

Figure 5.14: Total harvest weight in grams per month per vertical area [m^2] for each system

The Reclaimed Pallet system is by far the most productive system according to harvest per month per area. Because this system was not built and planted until April of 2012, the weight metric is not calculated over an entire year and did not include some of the colder months of January through April. These factors may contribute to its high score in this metric, but since the difference between this value (913 gr) and the next most productive system's value (Aria with 617 gr) is so marked, further work may indicate that the pallet system would be the most productive even when measured over an entire year.

Likewise, both the Domino Planter and the ELT systems were not planted with ornamentals until after June of 2012, so they were not measured during the warmest months of July and August at all. This may have contributed to their low productivity. Even when taking into account these inaccuracies, the low harvest yields per vertical area for both the Domino Planter and ELT systems indicated that they were not efficient food producers.

5.2.2 Influence of available root volume on food production

As described in Chapter 4, the parameter of available root volume showed significant variability between the systems. Some of the systems constrained each plant to a single compartment, and some allowed the roots to expand to adjacent spaces. Figure 5.15 shows the average root volume per plant as well as the maximal root volume available to each plant.

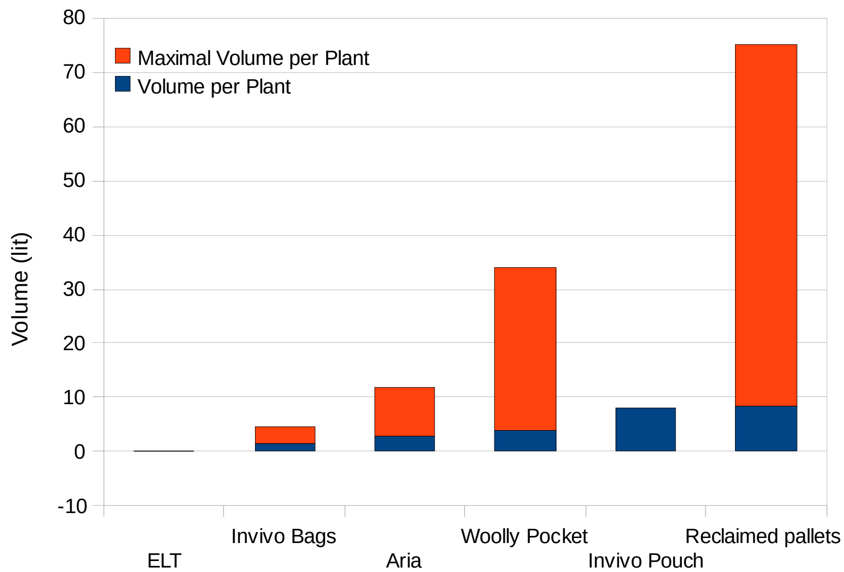

Figure 5.15: Available root volume per plant for each system

The total harvest comparisons between the different systems may be indicative of the influence that root volume had on crop yield. Only those systems that were found to be productive were included in this comparison based on values per vertical area.

- The Reclaimed Pallet system had 120 litres of growing substrate and covered a vertical surface area of 1.2 square metres.
- The Aria unit had 36 litres of growing substrate and covered a vertical area of 0.4 square metres.
- The Invivo Pocket had 24 litres of growing substrate and covered a vertical area of 0.4 square metres.
- The Woolly Pocket had 33.9 litres of growing substrate per unit and covered a vertical area of 0.65 square metres.

The resulting calculations of both growing substrate volume per vertical area per each system and of monthly crop weight per vertical area are presented in Table 5.1 and Figure 5.16. According to Figure 5.16, substrate volume is correlated with productivity. A system with slightly smaller substrate volumes produced smaller crop weights. To summarise, then, results showed that available root volume was a significant parameter when designing living walls for food production.

Table 5.1: Growing substrate volume per unit and per vertical area

	Substrate volume per unit [litre]	**Vertical area covered by unit [m^2]**	**Substrate volume per vertical area [litre/m^2]**	**Crop weight per vertical area [gr/m^2]**
Reclaimed Pallet	120	1.2	100	905
Aria	36	0.4	90	617
Invivo Pocket	24	0.4	60	469
Woolly Pocket	33.9	0.65	52	232

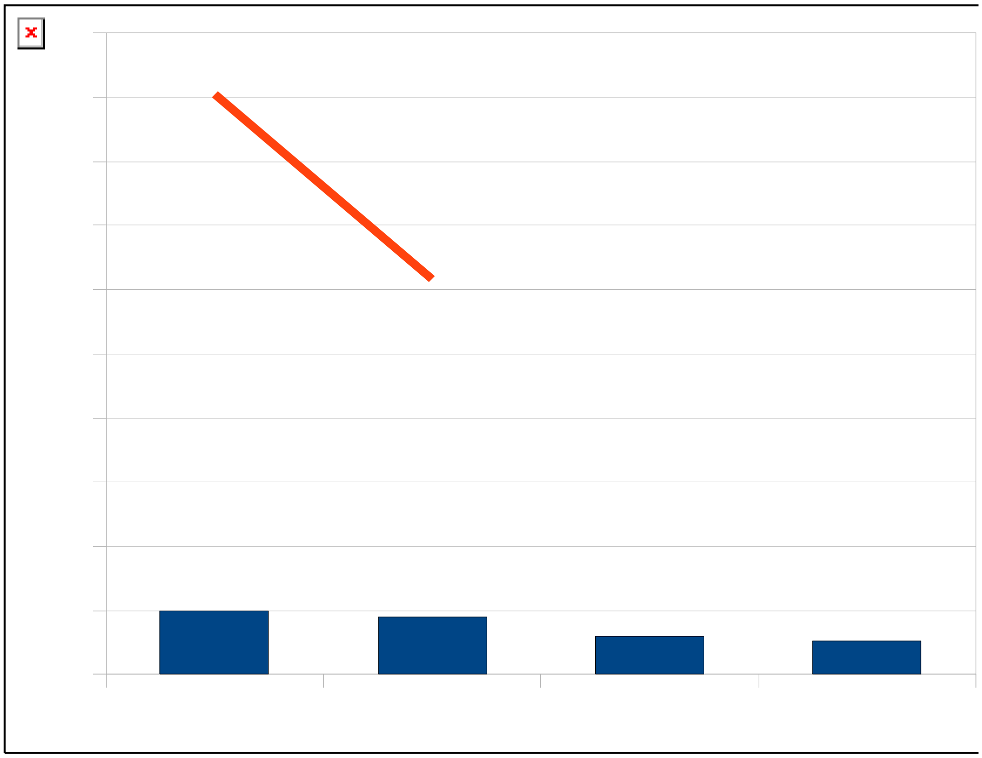

Figure 5.16: Substrate volume per vertical area [litre/m^2] and monthly crop weight per vertical area [gr/m^2] for each living wall system

5.2.3 Influence of plant selection on food production

The total harvest according to plant categories was described in section 5.1 for each of the living wall systems studied. Different living wall systems were variously well suited to grow different plant categories. See figures 5.17 to 5.20 for the distribution of harvest weight according to plant categories for each system.

Leaf vegetables were successfully grown in all but the ELT and Domino systems, where the leaf vegetables did not reach full size. Similar results were achieved with herbs. Brassicas were grown in all systems except for the ELT and Domino, but in both the Woolly Pocket and Reclaimed Pallet systems, they did not mature, probably as a result of the Woolly Pocket's limited amount of root volume and the Reclaimed Pallet's slanted planting angle. Because root vegetables could only be grown horizontally (or almost horizontally), only the Aria, Woolly Pocket, and Invivo Pockets facilitated their growth. Fruit vegetables and legumes required large root volumes to reach a productive size, and thus grew well in the Aria, Invivo Pocket, and Reclaimed Pallet systems (though they were at least partially successful in the Woolly Pocket system).

Table 5.2 provides a summary of the compatibility of vegetable categories with the various living wall systems. A type of vegetable is considered 'compatible' to a system if it was grown to maturity and produce harvestable foliage, roots or fruits. It is considered 'partially' compatible if it was productive but in smaller amounts, and the compatibility is marked as 'none' when the vegetable type was not productive at all for any reason.

Table 5.2: Compatibility of vegetable types to living wall systems. 'Compatible' marks producing harvest. 'Partially' marks limited productivity, and 'None' marks not reaching productivity.

Living Wall System	Leaf Vegetables	Herbs	Brassicas	Root Vegetables	Fruit Vegetables	Legumes
ELT	Partially	None	None	None	None	None
Domino Planter	Partially	Partially	None	None	None	None
Aria	Compatible	Compatible	Compatible	None	Compatible	Compatible
Woolly Pocket	Compatible	Compatible	Partially	Compatible	Partially	Partially
Invivo Pocket	Compatible	Compatible	Partially	Compatible	Compatible	Compatible
Reclaimed Pallet	Compatible	Compatible	Partially	None	Compatible	Compatible

Figure 5.17: Woolly Pocket system’s yield weight according to plant categories

Figure 5.18: Aria system’s yield weight according to plant categories

Figure 5.19: Invivo Triple Pocket system's yield weight according to plant categories

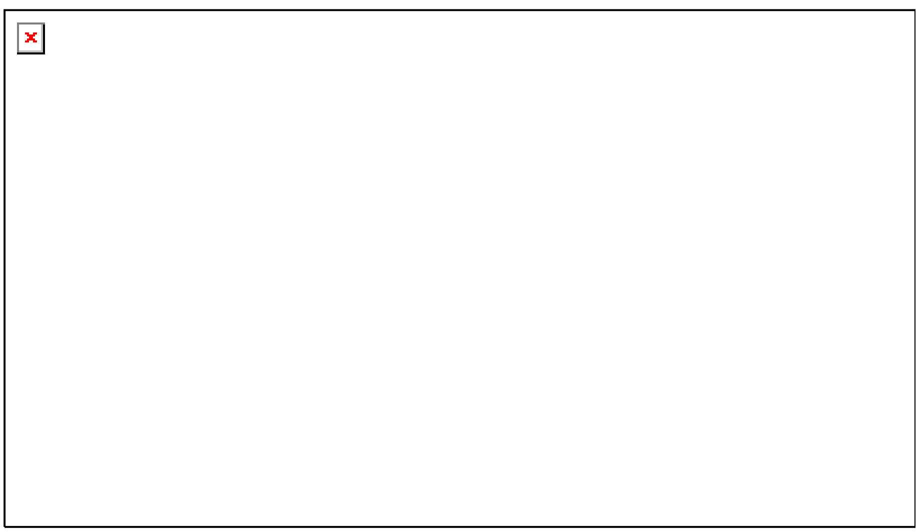

Figure 5.20: Pallet system's yield weight according to plant categories

5.2.4 Influence of planting angle on food production

As discussed in the methods chapter, the planting angle of living walls can be anything between "horizontal" (0º) and "vertical" (90º). The planting angles of the living wall systems in this study are presented in Table 5.3.

Table 5.3: Planting angle values per system

Living Wall System	Planting Angle
ELT	90º
Domino Planter	90º
Reclaimed Pallet	70º
Aria	30º
Invivo Pocket	0º
Woolly Pocket	0º

Some of the vegetables, especially root vegetables, were better started from seed, since transferring seedlings or root vegetables starters is believed to cause micro-wounds in the roots. Carrot and radish seeds were sown in all systems but they only grew in systems with a horizontal planting angle. Given the lack of light, shoots grew away from the ground (negative gravitropism) and were therefore unable to reach the substrate surface when it was vertically oriented. For the same reasons, it is expected that potatoes grown from bulbs (potato cuts) would not thrive in living walls with vertical or nearly vertical planting angles.

Many of the plants sown or transplanted at anything but a horizontal planting angle fixed their growth direction to be roughly vertical. The roots apparently grew mainly vertically as well (e.g., radish in Figure 5.22). In one case, an eggplant fruit growing in the Aria system eventually got heavy enough to break the plant's branch. It is not known if that single occurrence was coincidental or related to the slightly slanted planting angle (30º). None of the cabbage plants growing on the ELT, Domino Planter, or Reclaimed Pallet systems, all of which have a vertical or nearly vertical planting angle, yielded more than a few cabbage leaves or formed a proper cabbage-head. This may be related to the fact that the lower stem of the cabbage was relatively long and was bent to compensate for the planting angle.

Although only a few data points existed from this study (six values each for one of the six systems), the correlation between planting angle and productivity was plotted in Figure 5.23. The expected trend—that productivity would decrease as the planting angle increases—did not emerge from the data. On the contrary, the most productive was the Reclaimed Pallet system with a 70º planting angle. In fact, no obvious trend was detected. The results of this study indicate that the planting angle was not an important factor in the suitability of the living wall for food production.

Figure 5.21: Photo taken from above of newly germinated radish sprouts in the Woolly Pocket system. Germination from seed is possible in this system due to its horizontal planting angle.

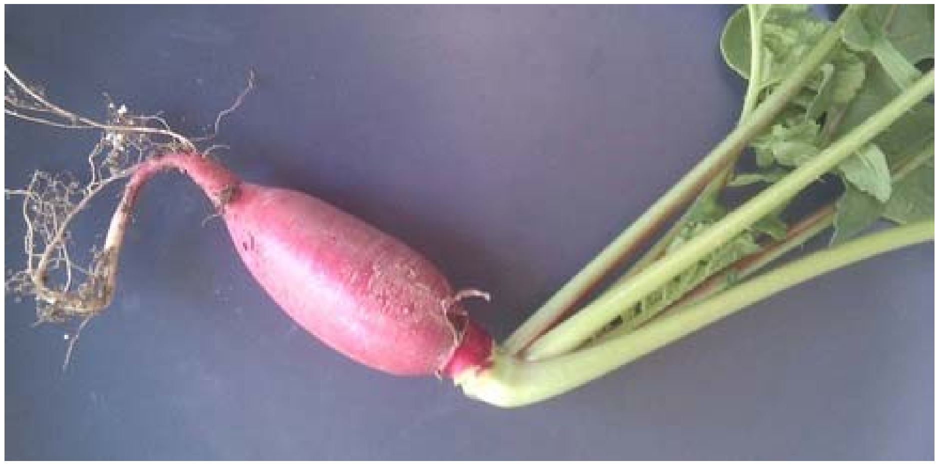

Figure 5.22: Radish from the Domino Planter with stems bent upward and roots bent downward

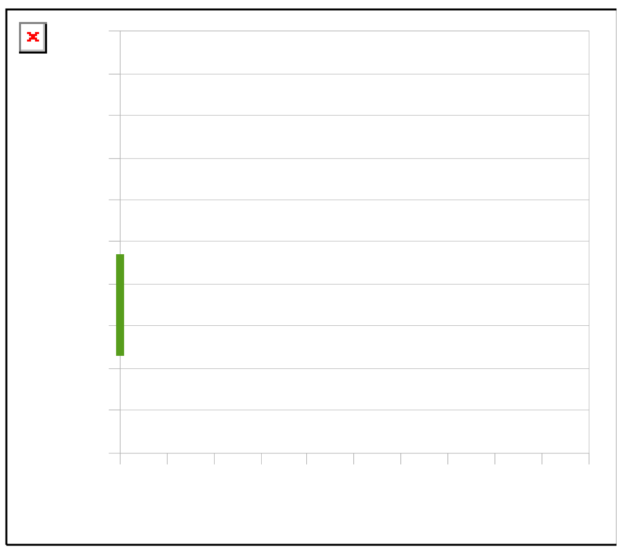

Figure 5.23: Planting angle (degrees from horizontal) is not strongly correlated with productivity

5.3 Comparing the Water Efficiency of Living Wall Systems

Conventional irrigation systems (such as sprinklers, drip irrigation, or wheel line systems) spread water over a crop that is horizontally dispersed over a large area. In living wall systems, the crop is dispersed vertically, and therefore gravity could be advantageous as the system is watered from the top and water cascades down to lower levels. This method did not yield the results expected in any but the Reclaimed Pallet System, primarily due to uneven distribution of water in the system's growing substrate. Too little irrigation dehydrated the lower-level plants. In some living wall systems, uneven distribution was affected by different circumstances causing dry conditions for the higher-level plants and overwatering of plants at the lower levels. It is assumed that the behaviour of different systems during watering sessions varies according to water delivery rates, growing-substrate drainage and uptake rates, saturation points, and system geometry. It should also be noted that as leaf vegetables grew and their leaves were regularly harvested, the root stock remaining in the growing substrate changed the system's water uptake characteristics over time, a factor which further complicates our understanding of optimal irrigation practices.

Once such difficulties were identified, the adopted irrigation system wherever possible was "one emitter per slot," thus ensuring that a predictable amount of water reached each plant. Watering times were adjusted to produce near-saturation of the growing substrate with minimum run-off or drainage. The irrigation schedules for the six systems are outlined in Table 5.4.

Table 5.4: Watering schedule during the summer months

System	Times per Day	Length in Minutes
ELT	3	1:30
Domino Planters	2	3:30
Reclaimed Pallets	1	9:00
Aria	2	4:00
Invivo Pocket	2	4:00
Woolly Pocket	2	4:00

Table 5.5 shows an estimation of the various systems' watering efficiency. The calculation took into account the total amount of daily watering and the volume of growing substrate in the system. This metric does not necessarily reflect the systems' true water-efficiency, since there could be a large volume of growing substrate that was not used by plant roots. However, this metric was chosen because calculating the amount of water per plant, for example, would favour systems that host many small plants. Since this study focused on food producing plants and a strong correlation was found between root space and productivity, it was more appropriate to account for root volume as the main factor for measuring vegetation potential.

Table 5.5: Amount of watering per volume of substrate

System	# of Drippers	Watering Time per Day [minutes]	Total Volume of Substrate [litre]	Daily Water per Substrate [litre/litre]
Reclaimed Pallet	12	9	120	0.03
Invivo Pocket	1	8	8	0.03
ELT	4	3	9.5	0.04
Domino Planter	2	7	9.4	0.05
Aria	12	8	36	0.09
Woolly Pocket	6	8	11.3	0.14

A more relevant metric for water efficiency for food producing living walls was the amount of water required on average to produce every kilogram of harvestable vegetables. Table 5.6 presents the results of that calculation, which was derived by dividing the total amount of water used per system during one month by the average harvest weight for that system per month. The Invivo Pockets and Reclaimed Pallet systems were significantly more efficient than the others with respect to the amount of water used per kilogram of material harvested.

Table 5.6: Water use per harvest weight

System	Water Amount per Average Harvest Weight [litre / kg]
Invivo Pocket	21
Reclaimed Pallets	25
Woolly Pocket	162
Aria	229
ELT	243
Domino	371

5.4 Comparing the Embodied Energy of Living Wall Systems

An important performance criterion was a system's environmental load up until the moment of installation. An analysis was done of the source materials required to manufacture the living wall systems and of the manufacturing process and the amount of transportation required to determine each system's embodied energy. The assessment of each system's manufacturing environmental load follows.

It is generally preferable to reuse or recycle source materials and to choose local products and low-energy manufacturing processes. In all but one case, the systems relied on plastic materials, but the source of the plastic and the manufacturing processes varied. Table 5.7 presents the different living wall systems sorted according to their environmental load in relation to manufacturing and transportation. Although this was not a quantitative assessment of emissions or energy consumption, the process of ordering the systems this way was a relatively straightforward one. To summarise this section, this study demonstrated that local material acquisition, local manufacturing, and reused/recycled material-use were feasible alternatives (at least in the Tel-Aviv context).

Table 5.7: Environmental load of materials, manufacturing, and transportation per system, ordered from lowest to highest

Living Wall System	Material Description & Source	Source	Manufacturing	Manufactured in
Reclaimed Pallet	Reclaimed wooden pallets, used flour bags	Reused	Material collection & low assembly energy	Tel-Aviv
Invivo Pocket	PE/PVC sheets from reclaimed billboards	Reused	Material collection & low manufacturing energy	Tel-Aviv
Woolly Pocket	Synthetic felt made of recycled PET bottles + PE layer	Recycled + new	Raw material & medium manufacturing energy	USA
Domino Planter	UV resistant PE sheets+ Fytocell foam	New	Raw material & medium manufacturing energy	Australia
ELT	HDPE	New	Raw material & high manufacturing energy	India
Aria	HPDE	New	Raw material & high manufacturing energy	USA

One of the most important parameters involved in determining a product's environmental load is its life cycle, including its longevity. The longer a system's potential to work and function, the better it was rated in terms of resource consumption, and therefore the next factor that was taken into consideration was the longevity of the system. Plastic based products are usually sensitive to UV radiation and should therefore either include UV protection or be used in shade (or shaded by the vegetation, where possible). Most of the purchased systems claimed to include UV protection (Aria, ELT, and Woolly Pocket). According to manufacturers, their expected life span should be between 15 and 20 years. Each system's end-of-life stage options (recycling/composting/landfill) is the last important factor assessed. Both PET and polyurethane could potentially be recycled. Table 5.8 summarises the life-cycle-related aspects of the various systems.

Table 5.8: Lifecycle aspects of the various living wall systems

Living Wall System	Expected Longevity [years]	End of Life
Reclaimed Pallet	3	Compost (90%)
Invivo Pocket	6	Landfill (10%)
Domino Planter	6	Landfill (100%)
ELT	15	Recyclable (95%)
Aria	15	Recyclable (95%)
Woolly Pocket	15-20	Recyclable (95%)

5.5 Comparing the User Experience of Living Wall Systems

Some of the living wall design parameters influenced the user experience of the living wall systems. This section reviews each of these design parameters.

5.5.1 Influence of substrate stability on user experience

The problem of the growing substrate's instability was relevant only in systems where the planting surface's orientation was not horizontal. Because the Aria system's planting surface was nearly horizontal, the problem was negligible for that system. The Reclaimed Pallet and the Domino Planter systems dealt with the issue by incorporating a soft sheet of material to hold the substrate in place, thus also rendering the problem virtually negligible. The study highlighted the importance of ensuring that the size of the planting holes/slits in non-horizontal planting surfaces was small enough to prevent the substrate from flowing out of the system.

5.5.2 Influence of system height on user experience

As was mentioned in the methods chapter, systems were installed in a band ranging from 30 to 200 centimetres in height from the ground. After initial growing iterations were performed on these systems, it became obvious that working in height zones that were either too low or too high demanded excess effort. In general, when plants can be approached, observed, treated, and harvested without bending over and without climbing a ladder or some other access system, then the routine growing tasks are not counter-balanced by physical exertion (i.e., bending over) or risk (i.e., climbing a ladder).

It was therefore determined that the ergonomic band for vertical vegetation growing should be between 30 centimetres and 200 centimetres. These values could be adjusted to suit individual growers. For example, wheelchair-assisted users could only access a narrower range. Available slots outside of this band were planted with low maintenance ornamentals, which augment the food production, deter pests, and/or attract pollinators.

5.5.3 Influence of substrate weight on user experience

During the living wall setup stage, it was apparent that the weight of the growing substrate was a significant parameter affecting the ease of setup. The growing substrate used in this study consisted of Perlite or compost or locally available loam, or some mixture of these. Filling the substrate in the living wall systems can be time-consuming, depending on the volume of the substrate and its weight. The task involved transporting the necessary amount of growing substrate to the site and then filling the units/modules of the living wall system as necessary. This was true for all cases except for the Domino Planter system. Its lightweight, sponge-like Fytocell growing substrate was pre-cut to the size of the planter.

The higher the living wall system was installed, the more difficult it was to fill it with growing substrate, but the height did not fluctuate significantly between the various systems. The amount of growing substrate required for each system did, however, vary largely between the systems (as discussed in the "available root space" section). In general, there is a trade-off between the volume of growing substrate in a living wall system and plant variety. Greater volume required more material, transport, and setup work. On the other hand, large growing substrate volume enables larger plant varieties to be selected and enhances crop yield. In addition, it was necessary to design the living wall system weight according to the physical limitations of the supporting structure (wall, fence, etc.), so if there were a weight limitation, lighter mixtures of growing substrate can be used in order to maximise growing substrate volume.

In Table 5.9, the volume of the growing substrate was calculated according to the dimensions of the living wall systems. The weight was calculated by assuming that the growing substrate was saturated, therefore the maximal weight of 1 litre of saturated compost or growing substrate was assumed to be 1.4 kilograms, and the weight of 1 litre of saturated Perlite was assumed to be 0.5 kilograms, according to Perlite specifications. Fytocell is reported to hold at least 60% air in volume even when saturated so the maximal weight of 1 litre of Fytocell is only

0.4 kilograms. In summary, heavier growing substrate weight decreased ease of use during the setup stage, although it generally increased productivity.

Table 5.9: Volume and weight of growing substrate in various living wall systems

Living Wall System	Type of Substrate	Substrate Volume per Unit [litre]	Number of Units	Total Substrate Volume	Max Substrate Weight
ELT	Perlite + compost	9.5	12	114	108
Domino Planter	Fytocell	9.4	16	150	60
Aria	Perlite + compost	36	6	216	205
Woolly Pocket	Perlite + compost	11.3	9	102	97
Invivo Pocket	Perlite + compost	8	18	144	137

5.6 Other Observations Related to Domestic Living Walls

5.6.1 Spacing between plants

The optimal number of plants per system and the spacing between plants were not relevant design decisions for all living wall systems. The Domino Planters had six minimally sized planting holes in fixed locations, so the number and location of plants was predetermined by the planter's structure. The Aria system's planting holes were larger (diameter=12.7 cm), but they still barely allowed more than one plant to be planted in each hole, so the number of plants and their location was not flexible either. The other systems allowed a reasonable amount of flexibility regarding the amount and spacing of planting.

The ELT system allowed planting in as many as 10 slots per panel, but that tended to create a very crowded patch. Because the ELT system was not designed for growing edibles, the vegetables were taken out and replaced with ornamentals. If the living wall is intended to feature ornamentals, the ELT system's potential density facilitates a greener appearance. The Invivo Pocket system allowed 1 to 3 plants in each pocket, although up to 10 carrots and radishes were grown in each pocket when raised from seeds. Having noted that, possible overcrowding resulted in the carrots only reaching a length of between 5 and 15 centimetres (see section 5.1.5). The Woolly Pocket was actually an elongated pocket with room for anything from 3 to 12 plants, somewhat similar to planting in a row in a field. The spacing between plants in the Woolly Pocket was done according to the recommended spacing of each plant, so that larger vegetables and herbs received 15 to 20 centimetres of space and smaller vegetables were spaced 5 to 10 centimetres apart.

The Reclaimed Pallet system had 18 openings in each pallet, each of which provided enough space for 1 or 2 plants. The actual location of the plant was set by cutting a slit in the used flour bag and planting through that slit. Eventually one slit was cut in each opening, such that 18 plants could be grown on each pallet face. Additional plants were planted through the top opening of the pallet, contributing another 3 to 6 plants to the total. Although this was a high planting density, few plants showed symptoms of lack of light or of root space, and most vegetables reached maturity in this system.

In summary, some of the living wall systems facilitated flexible planting densities. In these systems, higher density rarely had any adverse results on plant growth and development and usually resulted in better yields per vertical area.

5.6.2 Porosity of materials

Of those systems purchased, only the Woolly Pocket was made of a porous material. The synthetic felt allowed air and water to pass through it, except for the back area where the pocket is protected by an internal moisture barrier. However, the tendency for the porosity of the material to create an accumulation of salts and result in algae development was not observable at the beginning of the study. Some of the first Invivo Pockets were made with porous materials as well, and after a short while, brownish stains appeared on them—the result of fine substrate particles permeating the porous material. Figures 5.24 and 5.25 illustrate the stains on one of the Invivo pockets and on the Woolly Pocket system.

The staining did not influence the success of the plants, although it did affect the system's appearance. Note the brownish stains from the growing substrate on the light coloured material, and light stains from salt and algae on the dark brown material.

Figure 5.24: Invivo Pocket with brown stains

Figure 5.25: Woolly Pocket with algae and salt stains

The porosity of the material changed the amount of watering required, since it allowed more evaporation from the growing substrate than occurred with moisture retaining materials. In that sense, the disadvantages of using a living wall system made of permeable material (water inefficiency and visible stains) probably outweigh the advantages (allowing air flow to the roots).

5.6.3 Distance from ground level

The system's distance from the ground could influence plant health by creating a gap between the substrate in the system and soil-borne pathogens from the ground. Contact with the ground was only relevant to the Reclaimed Pallet system in this study. This may be why some of the plants in the lower part of the Reclaimed Pallet system became infested with fungi and had to be replaced.

5.7 Summary of the edible living wall study results

During the year-long case study of edible living walls, many design parameters were identified and investigated. The results unveiled a few correlations between design parameters and the performance of the living walls in terms of food production, water efficiency, embodied energy, and user experience. The study demonstrated that domestic living walls facing the equator (south in Tel-Aviv) could produce 100 to 1,000 grams of harvest per month per square metre of vertical area. The parameters correlated to productivity were the available root volume per plant, the choice of plants, and the total vertical area used for the living wall. There was much variance in water efficiency between the living wall systems.

It was shown that it was feasible to design living wall systems that were low in embodied energy by using local and preferably UV resistant materials, by utilising low-energy manufacturing processes, and by planning for long product-service life and optional recycling at end-of-life. In terms of user experience, it was preferable to locate living walls for food production at a convenient height of 30 to 200 centimetres from ground level, to plan the living wall system so that the growing substrate remains stable, and to consider ways to minimise setup effort.

6 Living Walls User Survey Results

This chapter presents the results of the living walls user survey. The survey addressed the second research question. The first set of questions in the survey collected data related to the living wall design and context parameter values, which was then used to map the design and context of the living walls referenced in the survey and identify living wall design schemes. The last set of questions, designed to estimate perceived performance parameter values, asked respondents to rate their living walls according to several performance parameters. The entire data set collected via this questionnaire was analysed to determine the influence of the values of the first set (design parameter values) on the values of the last set (perceived performance ratings) in order to establish how living walls' design parameters influenced the living walls' performance as perceived by the users.

This was the only study that evaluated social performance parameters such as assessing the living wall as 'relaxing and mood improving', 'enhancing sense of community', and 'educational'. Performance was subjectively estimated by living wall users. A table of the entire data set of responses can be found in Appendix D.

6.1 Findings Related to Living Wall Design Parameters

This section outlines the study's general findings related to living walls design parameter values, followed by an analysis of the responses to these questions, intended to identify particular design schemes of living walls.

6.1.1 Results limited to home, school, and office locations

Of the 66 respondents, 51 identified the site of their living wall as 'home' (77%), 9 as 'school/childcare centre' (14%), 4 as 'offices' (6%), and 2 as 'public spaces'. The options of 'shop', 'university', 'cafe/restaurant', or 'nursing home' were not selected by any of the participants. This suggests that the survey represented the opinions of users who had living walls in their own home well, and somewhat represented those with living walls in offices and schools. Scenarios beyond these were not covered, and the scope of the results should be considered valid only for the scenarios of domestic living walls and living walls in offices and schools.

6.1.2 High preference for herbs, medicinals, and edibles

The responses indicated that 71% of respondents' living walls grew herbs and medicinals. It should be noted that of these respondents, 47% (22 of 47) also indicated that they grew some ornamentals. Overall, an even split between ornamentals and edibles was expected, but results indicated that useful plants were strongly preferred.

6.1.3 Aesthetics as the leading motivation for using living walls

The responses to the multiple-choice question, What are your reasons for using a living wall?, clearly indicated that the leading reason for using living walls was aesthetics. 'It looks nice' was chosen by 43 respondents. 'It's green' and 'it saves floor/ground space' were chosen by 37 and 33 respondents respectively. Other reasons were chosen by less than half of the respondents. Complete results are charted in Figure 6.1.

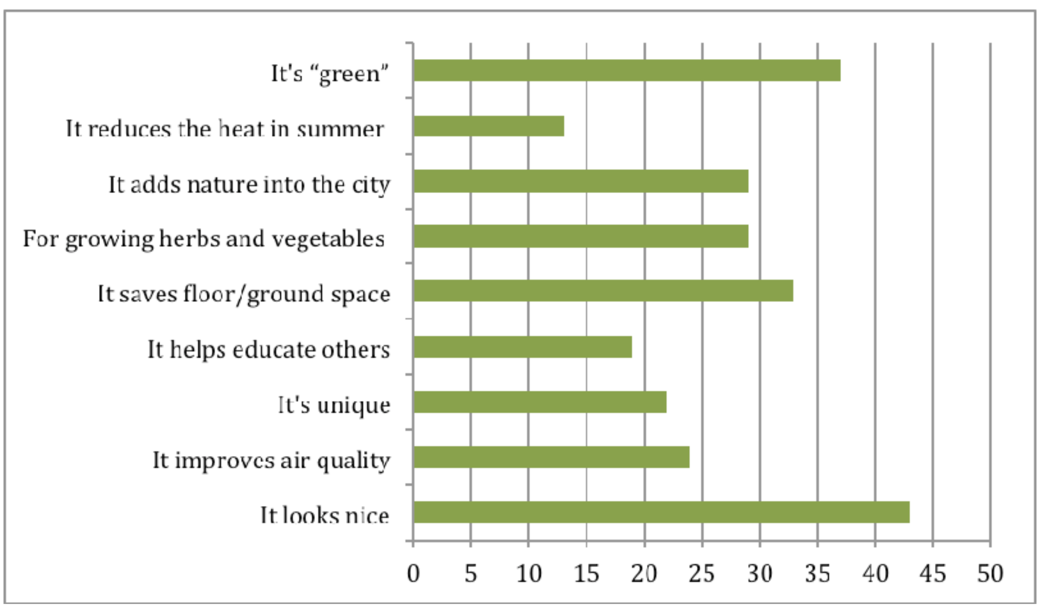

Figure 6.1: Reasons for using living walls according to survey results

6.1.4 Identifying living wall design schemes

In order to induce patterns from the results, the questionnaire results were grouped into several clusters of living wall characteristics (design and context parameter values) according to the following questions:

- Where is the living wall located? Possible answers were 'home', 'office', 'school/childcare', 'nursing home', 'university', 'shop', 'cafe/restaurant', 'public space', and 'other'.
- What is the type of unit that the living wall belongs to? Possible answers were 'private house', 'commercial building/unit', 'apartment', 'public building', and 'other'.
- What are the physical settings of your living wall? Possible answers were 'rooftop', 'outdoor wall', 'fence', 'balcony wall', 'balcony banisters', 'stair railings', 'indoors', and 'other'.

As mentioned, the vast majority of living wall installations were in homes (*n* = 52), some were in schools (*n* = 9), and a few were located in offices or public spaces (*n* = 5). Figure 6.2 presents a pie chart of the distribution of living wall locations. A clear feature of the structure of the data is the total absence of living wall projects in shops, universities, cafes, restaurants, or nursing home locations. The 'home' setting emerged as the largest cluster of participants (79%, *n* = 52); This number was further divided into the sub-clusters of 'apartments' (65%, *n* = 34) and 'private houses' (35%, *n* = 18).

Most respondents with apartment living walls indicated that the living wall was located on the balcony wall or balcony banisters (56%, *n* = 19. See Figure 6.3). Similarly, most private house respondents indicated that the living wall was located on the garden fence (72%, *n* = 13. See Figure 6.4).

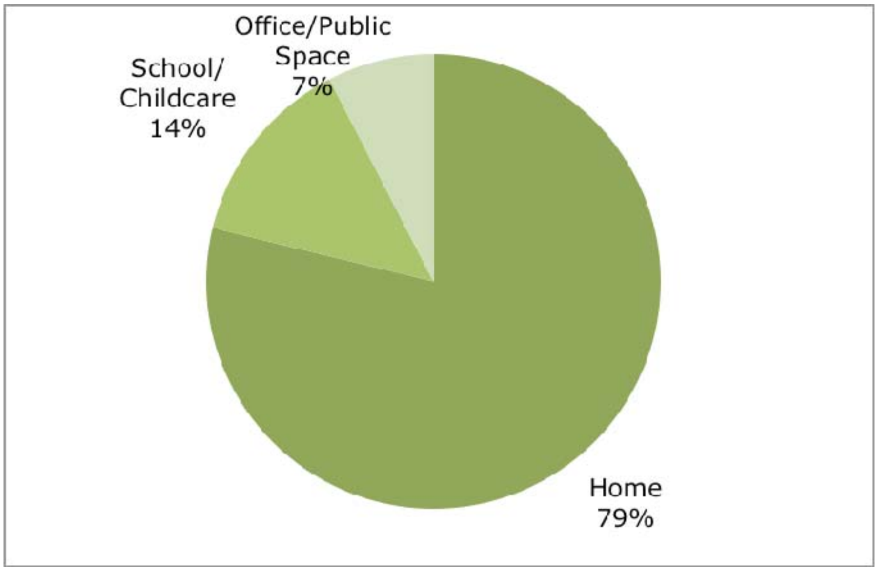

Figure 6.2: Distribution of living wall locations, according to 66 respondents

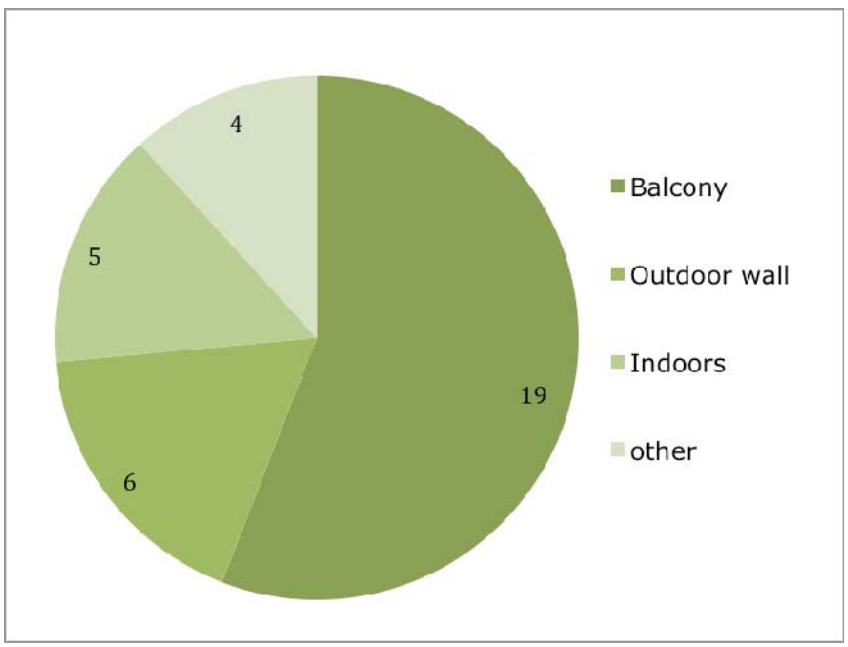

Figure 6.3: Settings of living walls in the home-apartment cluster, according to 34 respondents

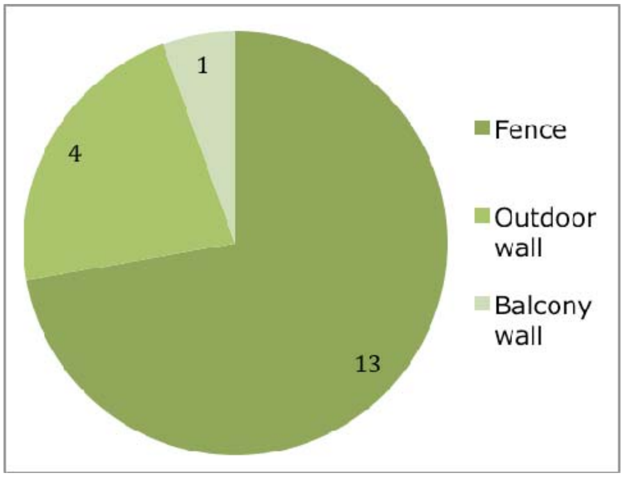

Figure 6.4: Settings of living walls in the home-private house cluster, according to 18 respondents

Of the nine 'schools/childcare centres' respondents (noted hereafter as 'schools'), six indicated that their living wall was located on an exterior wall (67%). The corresponding pie chart is presented in Figure 6.5.

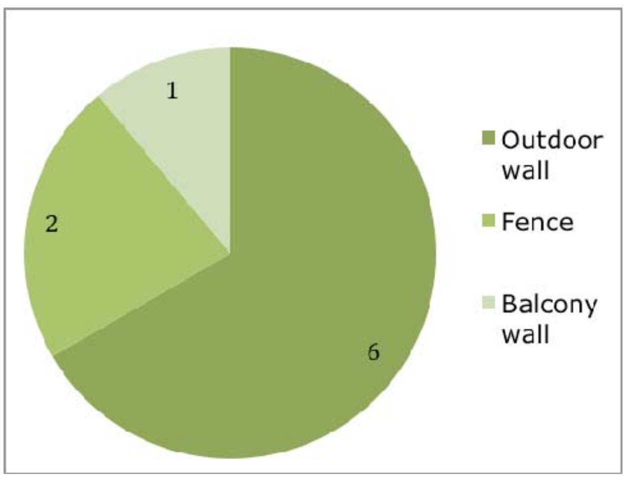

Figure 6.5: Setting of living walls in the school cluster, according to 9 respondents

From these results, three living wall schemes were identified:

- **apartments** with **balconies** used for living walls;
- **private houses** with living walls on their **garden fences**; and
- **schools** or daycare centres with living walls on **exterior walls**.

The following sections detail each of the three schemes with respect to their physical and architectural characteristics, motivational perspectives, and related user experiences.

Living walls in apartment balconies

The most common living wall scheme, according to the results, is a small-sized wall covering an area of approximately two to three square metres (average of answers) that uses between two and eight living wall units (74%) and is located on apartment balconies. Such apartments would be situated in a residential inner city area in Tel-Aviv, in a multi-story building, with the living wall installed on either the balcony wall or the balcony banisters (possibly on both, although this response was not included as an option in the questionnaire).

Living walls were usually hand-watered (53%) but could be automatically drip-irrigated (37%), and they were either half–shaded or got full sun (79%). Balcony plants were usually herbs and medicinals (79%), leafy vegetables (58%), annual flowers (42%), and fruit vegetables (37%). The living wall was usually maintained by the owner who was often a novice gardener (68%). The most prevalent reasons for using living walls in apartment balconies were that the living wall saves floor space (68%), is 'green' (58%), 'adds nature' to the city (53%), grows herbs and vegetables (53%), and 'looks nice' (53%).

Figure 6.6: A small living wall located on balcony banisters of an apartment in Tel-Aviv

Private houses with living fences

The second scheme was small- to medium-sized living walls covering an area of approximately three to four square metres (average of answers) that used between two and eight living wall units (62%). This type of living wall was located on fences that enclose a backyard or garden of a private house that would most likely be situated in a residential, suburban area of Tel-Aviv.

Here, too, living walls were usually hand-watered (54%) but they could be automatically drip-irrigated (31%), and they were either half–shaded or got full sun (85%). Plants for living walls of this scheme were usually herbs and medicinals (62%), leafy vegetables (62%), fruit vegetables (46%), and perennials (38%). They were usually maintained by an owner who was more likely to be an experienced gardener (54%).

The most prevalent reasons for using a living wall on the fence of a private house were that the living wall 'looks nice' (62%) and that it grows herbs and vegetables (31%).

Figure 6.7: A medium-sized living wall set on an exterior fence in the Tel-Aviv area

Living walls on exterior walls of schools

The third scheme was living walls in public buildings, where the living wall was located on an exterior wall of the building. Of the seven responses that matched this scheme, six were schools or childcare centres. The building itself could be either single- or multi-story and had a common backyard.

The living wall was usually medium- to large-size and covered an area of approximately five square metres. It was constructed of nine or more pockets/units and was most likely located in full sun. Students and/or teachers, most of whom were novice gardeners (57%), maintained them. An automatic drip irrigation system was used (100%), and the principal plants in the living wall were herbs and medicinals (86%), succulents (57%), perennials (57%), and flowers (57%).

The most prevalent reasons for having a living wall on the exterior wall of a public building were that the wall helps educate others (100%), 'looks nice' (100%), 'adds nature' to the city (86%), is 'green' (86%), and improves air quality (86%). This cluster of respondents each chose many reasons, and all of the suggested reasons for having a living wall were selected by at least five of the seven respondents. This may indicate that the users of living walls in this cluster were generally more knowledgeable about their living walls.

Figure 6.8: A large living wall set on the exterior wall at a childcare centre in the Tel-Aviv area

6.2 Findings Related to Living Walls' Perceived Performance

The performance of the living walls, as perceived by their users, was assessed by the last set of questions. Participants were asked to rate their living walls on a scale of one to five according to each performance parameter, where 1 was 'Not at all' and 5 was 'Very much'. The average results for each of the parameters are presented in Table 6.1 (also see Figure 6.9 for a bar chart representation of the results). This section presents general findings related to the participants' responses to these questions.

Table 6.1: Average rates of living wall performance as perceived by the respondents (*n* = 66)

Performance Parameters	Average Rating [1-5]	Variance Standard Dev.
Energy Efficient	2.94	2.12
Water Sensitive	3.09	1.41
Low Embodied Energy	3.26	1.67
Biodiversity Enhancer	2.82	2.06
Urban Agriculture Facility	3.62	2.42
Enhancing Sense of Community	2.91	2.39
Educational	3.61	2.03
Relaxing & Mood Improving	4.32	0.87
Overall Successful	4.14	0.67

6.2.1 High perceived performance, particularly for social benefits

Overall, respondents were highly satisfied with their living walls. The average perceived overall performance of the living walls (rating the living wall as 'overall successful') was 4.14 (on a scale of 1 to 5). Respondents also gave high ratings (>3) to most of the specific perceived performance parameters, and awarded a particularly high performance rating for 'relaxing and mood improving' (average of 4.32 on a scale of 1–5). The parameters that were rated lower (<3) were 'enhancing sense of community', 'biodiversity enhancer', and 'energy efficient'. See Figure 6.9 for average values of all the responses to the five-level Likert question, 'How would you rate your living wall as:'.

6.2.2 Social benefits rated higher than environmental benefits

As shown in Figure 6.9, respondents, on average, ranked the social-related performance parameters (e.g., 'relaxing and mood improving' and 'educational') higher than the environmental performance parameters (e.g., 'energy efficient' and 'biodiversity enhancer'). Living walls' performance as 'relaxing and mood improving' was by far the most highly rated response. The next most highly rated of the performance parameters were 'educational' and 'urban agriculture facility'. This indicates that respondents were, on average, more aware of the social benefits of living walls than of the environmental benefits.

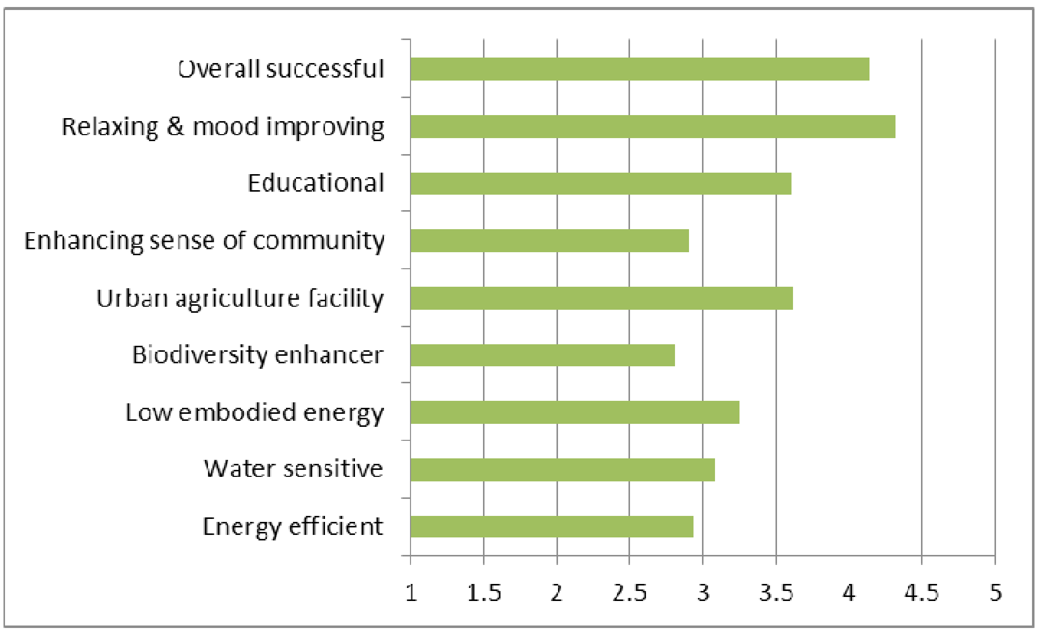

Figure 6.9: Average perceived living wall performance rates [1–5], for various parameters (n = 66)

6.3 Parametric Analysis of Living Wall Design's Impact

The main objective of the survey was to study living walls' design parameters and how their various values related to the perceived performance of the living wall. This was accomplished by analysing the difference in perceived performance ratings between groups of responses that had different design parameter values. In order to examine whether a design parameter impacted the perceived performance, the responses were grouped according to each design parameter value or set of values, and the average performance rating was then calculated for each group. The difference in ratings between the groups was considered statistically significant when the result of the *t* test value was smaller than 0.05.

6.3.1 Interior living walls better at enhancing sense of community

Respondents were asked about their living wall's location and were able to choose one of the following options: 'outdoor wall', 'balcony wall', 'balcony banister', 'fence', 'stair rails', 'rooftop', and 'indoors'. The responses were grouped into interior or exterior locations (the latter included all but 'indoor' locations). In only one performance parameter was the difference between the groups statistically significant. The interior living walls were rated significantly higher (p = 0.023) with respect to enhancing the sense of community. The other differences in perceived performance between the two groups were not statistically significant (probably because there were only 6 respondents with interior living walls), but they did show that the exterior living walls were rated higher on their environmental performance parameters ('energy efficient', 'water sensitive', 'low embodied energy', and 'biodiversity enhancer'). The results are shown in figures 6.10 and 6.11. Although it was expected that exterior living walls would be perceived as better in terms of energy efficiency, biodiversity enhancement, and water sensitivity, it was not expected that interior living walls would be perceived as community promoters and as more educational.

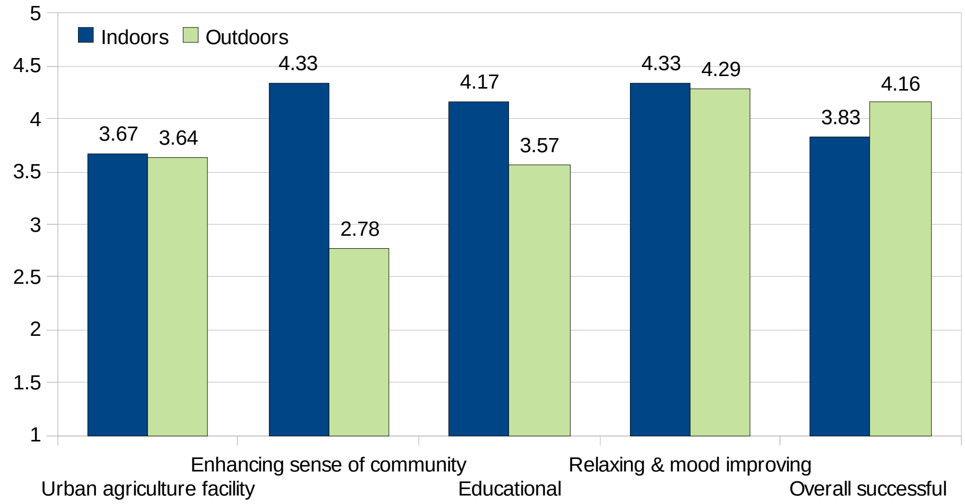

Figure 6.10: Average perceived performance ratings of living walls, comparing interior vs. exterior living walls

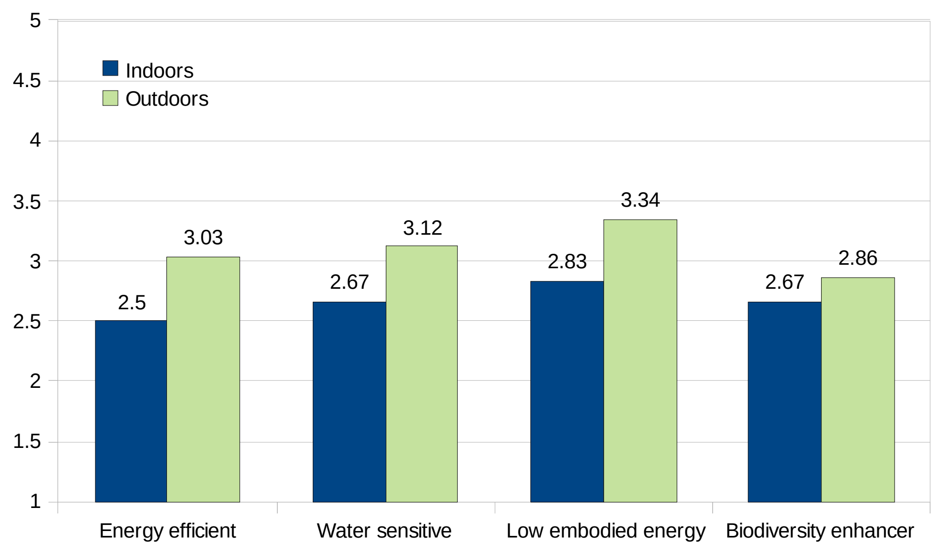

Figure 6.11: Average perceived performance ratings of living walls, comparing interior vs. exterior living walls

6.3.2 Living walls' size influenced their perceived performance

The size of the living wall was indicated by choosing one of four options: '1–2 m^2', '3–5 m^2', '5–10 m^2', and 'more than 10 m^2'. The results were grouped into two larger groups: small living walls (1–5 m^2) and large living walls (more than 5 m^2). Perceived performance was then grouped according to these two sizes, and the results are shown in Figure

6.12. The only parameter for which the small living wall was rated higher was 'urban agriculture facility' (3.80 vs. 3.00), but this difference was not statistically significant (p = 0.084). This may be because edible living walls are expected to require higher maintenance, and small living walls are easier to attend and maintain.

Respondents rated the large living walls higher in all other parameters, and significantly higher in terms of 'enhancing sense of community' (p = 0.001), 'relaxing and mood improving' (p = 0.021), and 'overall successful' (p = 0.007).

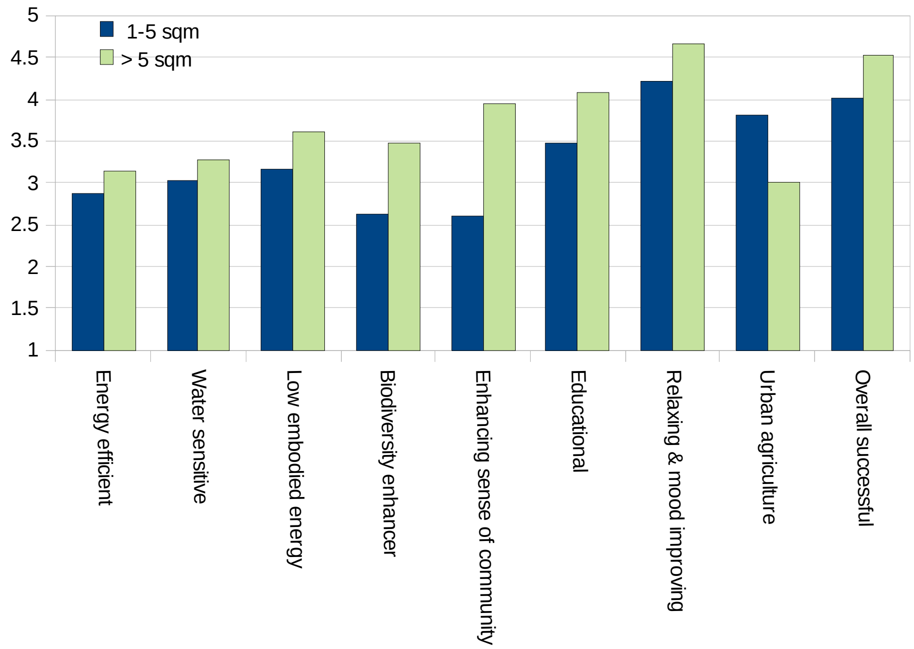

Figure 6.12: Relationship between living wall size and perceived performance parameters

6.3.3 Domestic living walls less educational and less community oriented

Respondents were asked to indicate the site of their living wall from one of the following options: 'home', 'office', 'school/childcare centre', 'public space', and 'other'. Those results were grouped into two larger groups: home and other. Then all responses were grouped according to these two values and the perceived performance compared between the two groups, as shown in Figure 6.13.

The only performance parameter in which the domestic living walls were rated higher than the rest was 'energy efficient' (3.10 vs. 2.36, but this difference was not statistically significant (p = 0.086). Respondents rated domestic living walls lower in all other parameters and rated them significantly lower in terms of 'enhancing sense of community' and 'educational' (p < 0.001). Domestic living walls were rated similarly to the rest of the living walls in the 'overall successful' parameter (4.1 vs. 4.36).

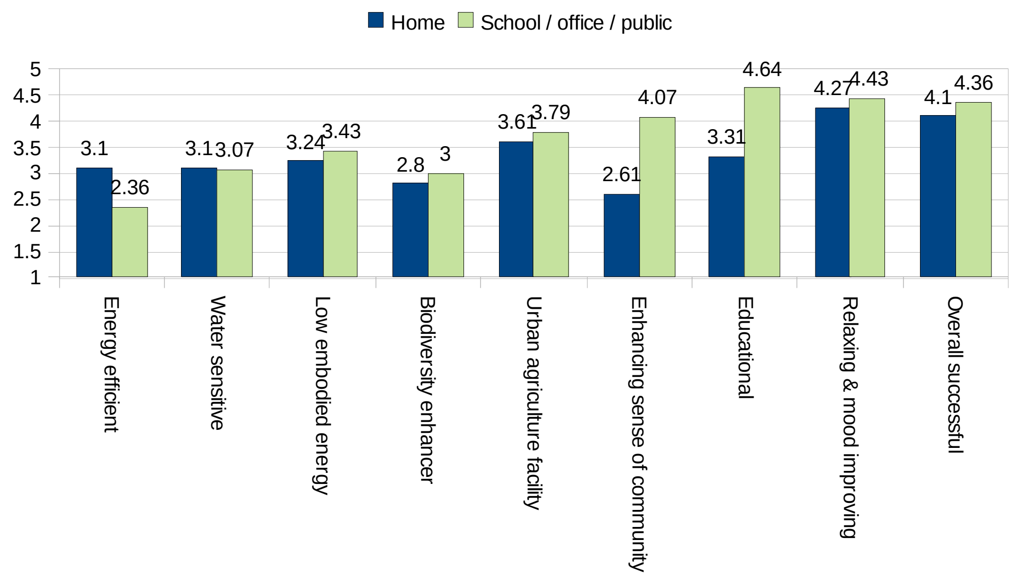

Figure 6.13: Average rating of perceived performance parameters for domestic living walls compared to other living walls

6.3.4 Living walls in residential areas less educational and community oriented

Respondents were asked what term best described the area in which the building's living wall was situated. Since most respondents described a living wall located at home, it is not surprising that the majority of results were 'residential area' (n = 53). The results were grouped by respondents who chose 'residential area' and those who chose any other option, and the average performance ratings were compared. The only statistically significant differences were in terms of 'educational' and 'enhancing sense of community', where the residential living walls were perceived as less successful. Complete results are presented in Table 6.2.

Table 6.2: Living walls located in residential areas were rated lower in education-related and community-oriented performance parameters

	Enhancing Sense of Community	**Educational**
Residential	2.70	3.36
Others	3.77	4.62
p	0.027	0.000

6.3.5 Living wall system related to food production performance

Respondents were asked to select what system they were using for their living walls from the following list: 'Invivo pouches', 'pallet system', 'climbers/vines', and 'other'. The results were grouped by the systems (except for the 'other' option), and the average 'overall success' rating was then compared between the three groups. The results did not show a statistically significant difference in users' perception of overall success between those three groups ($p > 0.20$).

One of the findings of the edible living wall study was that the system used for the living wall influenced its productivity. A subsequent analysis compared the average 'urban agriculture facility' rating between the three groups. Living walls using Invivo pouches and pallet systems received average ratings as an 'urban agriculture facility' of 4.03 and 3.89 respectively. Living walls based on climbers and vines had a significantly lower rating of 2.80. This meant that users of living walls based on climbers or vines rated their living wall as less successful as urban agricultural facilities than did users of other living wall system types. See Figure 6.14 for the comparison between the three groups.

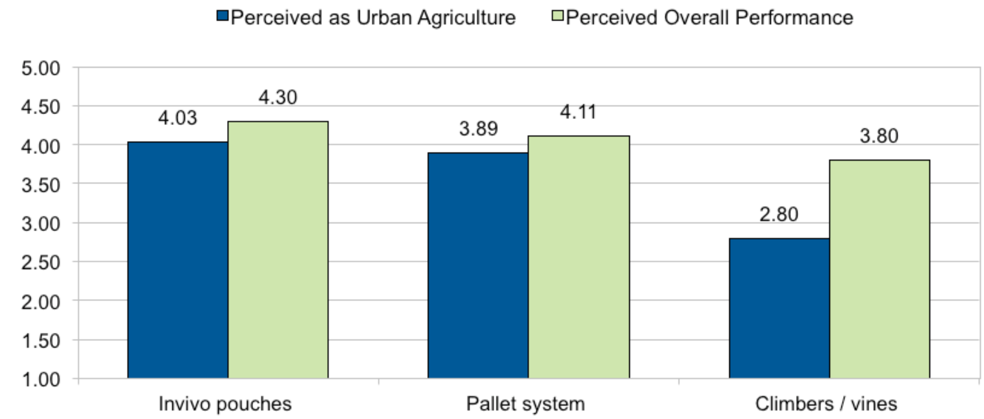

Figure 6.14: Comparison of the average rating of living walls as generally successful and as urban agriculture for living walls using various systems

6.3.6 Plant selection not related to perceived performance

The fact that different plant selections did not significantly alter the users' perception of the living walls as being successful was surprising. Figure 6.15 shows the average perceived overall performance levels for each plant category.

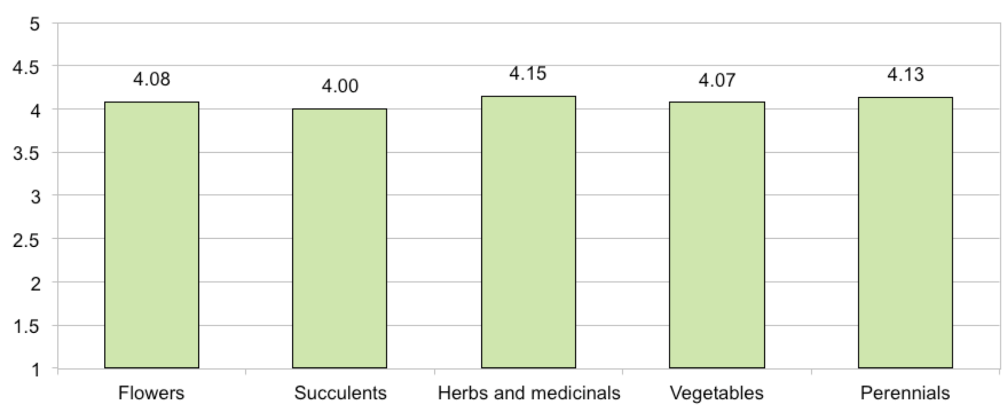

Figure 6.15: Average ratings of living walls as 'overall successful' according to plant types

One of the performance parameters that changed significantly with plant selection was the 'urban agriculture facility'. Figure 6.16 shows that living walls with perennials were considered significantly (p =0.047) less suitable for agriculture. Living walls with other types of plants were rated as more agricultural, and in those cases, the differences between the types was not significant (p > 0.05). Although many edible herbs are perennials, the respondents of the survey probably did not plant edible perennials in their living walls, and therefore rated their living wall as not suitable for urban agriculture.

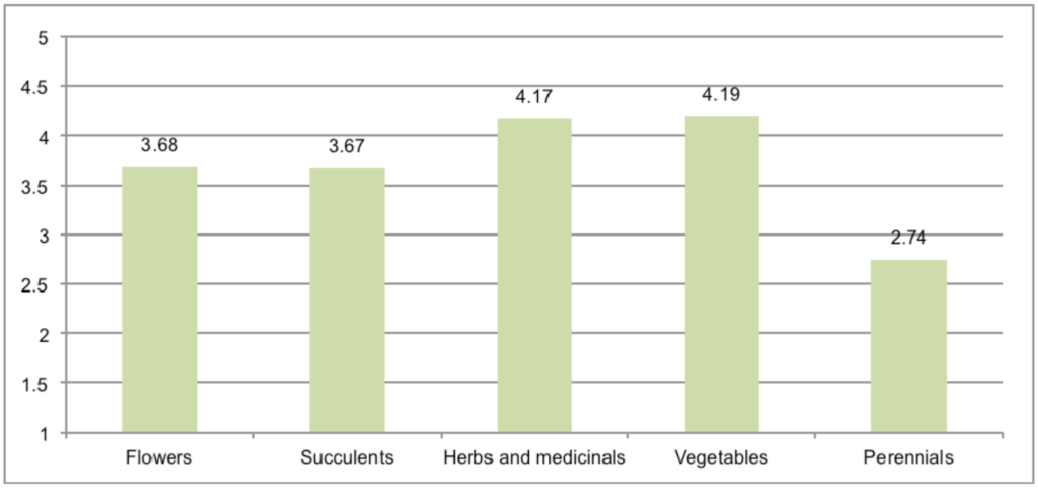

Figure 6.16: Average ratings of living walls as agricultural according to plant type

The second statistically significant finding related to plant selection was that living walls with succulents were considered more ‘water sensitive’ (average rating 3.60 vs. 2.90, *p* =0.017). This result was not surprising as succulents are usually water efficient. To summarise, no significant correlation was found between plant selection and the participants’ perceived performance of the living wall.

6.3.7 School wall design scheme perceived as slightly better

The results were grouped according to the three emergent living wall design schemes:

1. apartment balcony,
2. private house fence, and
3. school exterior wall.

Responses describing living walls that did not fit these three design schemes were not used in this analysis. The average perceived performance rates were compared between the three groups as shown in Figure 6.17. The rating of 'overall successful' parameter was similarly high in all three schemes (4.05, 4.17, and 4.43). The school wall design scheme was rated higher than 3 (in 1-5 scale) in all parameters except for 'energy efficient' and 'biodiversity enhancer'. The apartment balcony design scheme was rated high in all parameters except for 'biodiversity enhancer' and 'enhancing sense of community'. The private house fence scheme was rated high only in 'relaxing and mood improving' (in addition to the 'overall successful').

When comparing the design schemes, the school design scheme was rated significantly higher ($p < 0.01$) than the other design schemes in both the 'educational' (4.00) and 'enhancing sense of community' (4.71) parameters. The private house fence design scheme was rated significantly lower ($p < 0.05$) as 'educational' (2.67) and as 'low embodied energy' (2.58) when compared to the other schemes.

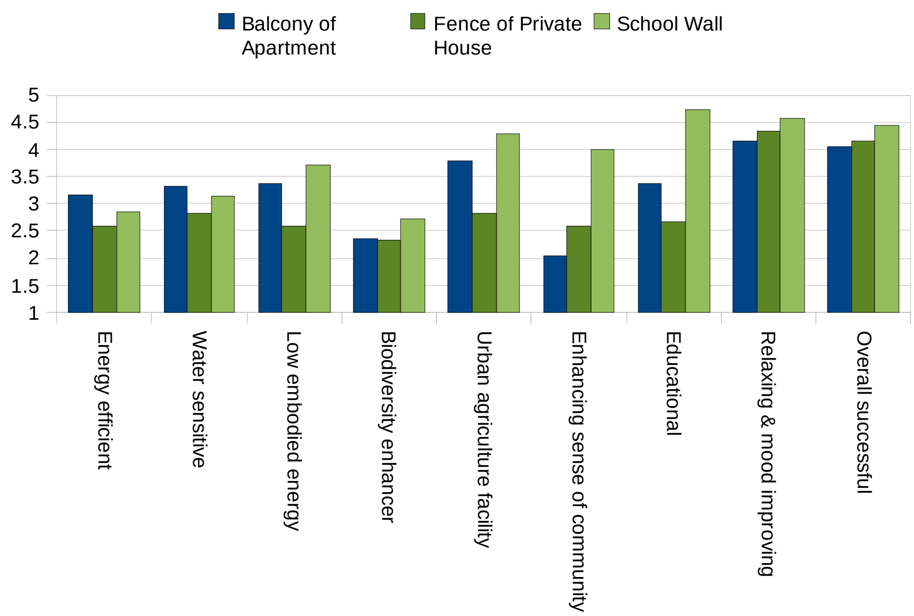

Figure 6.17: Average perceived performance ratings of living walls per design scheme

6.3.8 Apartment balcony and school wall design schemes most suitable for food production

According to the edible living wall study results, domestic living walls, whether on apartment balconies or on a private house’s fence, would be more efficient food producers since they can accommodate accessible living wall systems. Living walls that belong to the apartment balcony design scheme or to the school wall scheme were rated higher by their users as an 'urban agriculture facility' (see Figure 6.17). This is probably because living walls on balconies are highly accessible and allow their users intimate interaction. Living walls located on the exterior walls of schools were probably designed to be accessible to students in order to enhance interaction and achieve educational goals, and this setting allowed school living walls to function well for food production if edible plants were grown.

6.4 Living Walls Suitable for Food Production and Building Energy Savings

The results of the other studies conducted in this research—building energy simulation, and edible living wall study—were used to group the responses of the survey in order to perform additional parametric analysis of the data.

6.4.1 Living walls suitable for thermal energy savings rated higher

For living walls to save building cooling energy well, they should cover a significant portion of the building's exterior walls. In addition, the living wall should face the equator, west, or east (see Chapter 7). The results of the survey showed seven cases in which the living wall spanned 'more than 10 sqm'. Of these, only five living walls covered an exterior or balcony wall. Only three of these covered an equatorial (south-facing) wall, while one covered a west-facing wall. It is therefore expected that most of the living walls included in this survey did not contribute significantly to building energy savings.

The average perceived success of the four eligible living walls was 4.50 (n = 4), a figure that was higher than the average of the other living walls, which was 4.11 (n = 62). The average rating of these living walls as energy efficient was 3.25 (n = 4), higher than the 2.92 (n = 62) average of this rating for the other living walls. The differences between the groups was not statistically significant (p > 0.25), probably due to the small size of the first group (n = 4). Table 6.3 outlines the comparison between the two groups.

Table 6.3: Living walls suitable for building energy savings were rated higher, on average, than the other living walls (though not statistically significant)

	Energy Efficient	Overall Successful
Large, Exterior, Equatorial / West Facing	3.25	4.50
Other Living Walls	2.92	4.11

The results of this analysis are not strong because of the small number of large living walls that the survey covered, but they do reinforce the results of the thermal simulation study.

6.4.2 Living walls suitable for food production rated higher

According to the edible living wall study, several living wall design parameters were essential for food production. Some of these parameters were covered by the survey and were used to divide the results into two groups: edible living walls and others. The edible living walls were ones that did not use a 'climbers/vines' system, were not interior, received at least three hours of sun per day, and were planted with 'vegetables' or 'herbs and medicinals'.

According to these criteria, 37 of the 66 living walls could be classified as edible living walls. The average perceived overall success of the edible living walls was 4.24, not significantly higher than the average of the other living walls (3.96, $p = 0.19$). The average rating of these living walls as an 'urban agriculture facility' was 4.19. This is significantly higher than the average of this rating for the other living walls (2.97, $p < 0.01$).

Table 6.4: Living walls suitable for food production were rated higher, on average, than the other living walls

	Perceived Overall Success [1–5]	Urban Agriculture Rating [1–5]
Edible Living Walls	4.24	4.19
Other Living Walls	3.96	2.97

6.5 Summary of Survey Results

The purpose of the survey was to:

- map the design decisions of the living walls that participated in the survey and identify urban living wall design schemes,
- estimate the performance of the living walls, according to user perception, and
- understand the influence of living wall design decisions on the living wall's perceived performance.

The survey covered a majority of domestic living walls, although living walls located in schools and offices were also included. The respondents' living walls were clustered into three living wall design schemes. Detailed descriptions of the three schemes emerged from the survey, thereby enhancing the general understanding of design decisions for living walls. It was found that living wall users were generally satisfied with their living walls and rated their performance highly in most instances. Living walls' social performance was generally rated higher than was their environmental performance.

Each living wall design scheme was also analysed for its perceived performance. The most highly rated design scheme was that of a living wall on the exterior wall of a school. Table 6.5 summarises the characteristics of the three living wall design schemes identified using the survey and their perceived performance. It is possible that the importance of the personal attitude towards the living wall and the sense of perceived success were more apparent because the survey's results were skewed toward a majority of small, domestic living walls.

Table 6.5: Summary of three design schemes of urban living walls and their characteristics, according to the survey responses. Only perceptions with average rating>3 are included

	Apartment Balcony	Private House Fence	School Exterior Wall
Location of Living Wall	balcony	fence	exterior wall
Approximate Size (average)	2–3 m^2	3–4 m^2	5 m^2
Plant Selection	herbs & medicinals (79%), leafy vegetables (58%), annual flowers (42%), fruit vegetables (37%)	herbs & medicinals (62%), leafy vegetables (62%), fruit vegetables (46%), perennials (38%)	herbs & medicinals (86%), succulents (57%), perennials (57%) & flowers (57%)
Maintenance	owner - novice gardener (68%)	owner - experienced gardener (54%)	students and teachers - novice gardeners (57%)
Irrigation	usually hand watered (53%), maybe drip irrigation (37%)	usually hand watered (54%), maybe drip irrigation (31%)	drip irrigation (100%)
Living Wall Perceptions (average rating on 1-5 scale)	relaxing and mood improving (4.16)	relaxing and mood improving (4.3)	relaxing and mood improving (4.57)
	urban agriculture facility (3.79)		educational (4.71)
	educational (3.37)		urban agriculture facility (4.29)
	low embodied energy (3.37)		enhancing sense of community (4)
	water sensitive (3.32)		low embodied energy (3.71)
	energy efficient (3.16)		water sensitive (3.14)

In terms of the relationship between living wall design decisions and perceived performance, several relationships were found between design parameters and perceived performance parameters. The list of findings is presented in Table 6.6. In addition to the statistically significant findings (presented in bold font), some findings that were significant are included in the table, although they require further corroborative data.

Table 6.6: Living wall perceived performance parameters and their related design parameter values

Perceived Performance Parameters	**Related Design Parameter Values (statistically significant results in bold)**
energy efficient	exterior, **school exterior wall or apartment balcony**
water sensitive	exterior, **succulents**
low embodied energy	exterior, **school exterior wall**
biodiversity enhancer	exterior
urban agriculture facility	living wall system=pockets or pallets, **not perennial plants,** small
enhancing sense of community	**large,** **interior,** **not domestic,** **not in residential area,** **school exterior wall**
educational	**not domestic,** **not in residential area,** **school exterior wall**
relaxing & mood improving	**large**

7 Thermal Energy Simulation Results

The building energy simulation study of living walls answered the third research question. This study describes relationships between living wall design and context, and building thermal energy performance, by parametrically studying how changes in living wall parameter values influence energy consumption. More than 200 simulations supplied the data that was used to answer the third research question.

First, a baseline scenario for the thermal simulations of living walls was established by setting typical values for the various design parameters. A thermal simulation was then executed with those baseline values and its results were compared to the results of an identical simulation without vegetation cover. Section 7.1 presents the results of this comparison, supplying information on the extent to which living walls can confer building energy savings. The baseline simulation results were also used to compare the results of subsequent simulations, using different values for the living wall parameters being studied. Sections 7.2 through 7.5 present those results, focusing on four aspects of living wall design decisions that showed a significant influence on building energy consumption: orientation, vegetation, growing substrate, and irrigation. See Appendix B for the simulations' raw results.

7.1 Cooling Energy is More Important than Heating Energy

When using the baseline parameter values with the Tel-Aviv weather file, the energy required to cool the bare building every year (5,356,068 kJ) was greater than the amount needed to cool the same building covered with vegetation (3,815,101 kJ). Similarly, the amount of energy required to heat the bare building yearly (618,403 kJ) was greater than the amount needed to heat the same building covered with a green roof and living walls (607,597 kJ). Table 7.1 presents this set of results, which reflect the energy required to maintain thermal comfort during daytime hours between 08:00 and 18:00.

Results show that most of the energy required to maintain thermal comfort during the day was cooling energy. The vegetation cover saved 1,540,967 kilojoules per year for cooling compared to only 10,806 kilojoules per year for heating. In the Mediterranean Tel-Aviv climate conditions, heating energy savings were much less significant than cooling energy. Figure 7.1 identifies the savings in cooling energy as a large gap between the grey and the green columns, whereas the heating savings are minute.

Table 7.1: Yearly heating and cooling energy savings in Tel Aviv

	Cooling Total [kJ]	Heating Total [kJ]
Bare Building	5,356,068	618,403
Building with Green Roof & Vertical Vegetation	3,815,101	607,597
Energy Savings Compared to Bare Building	1,540,967	10,806

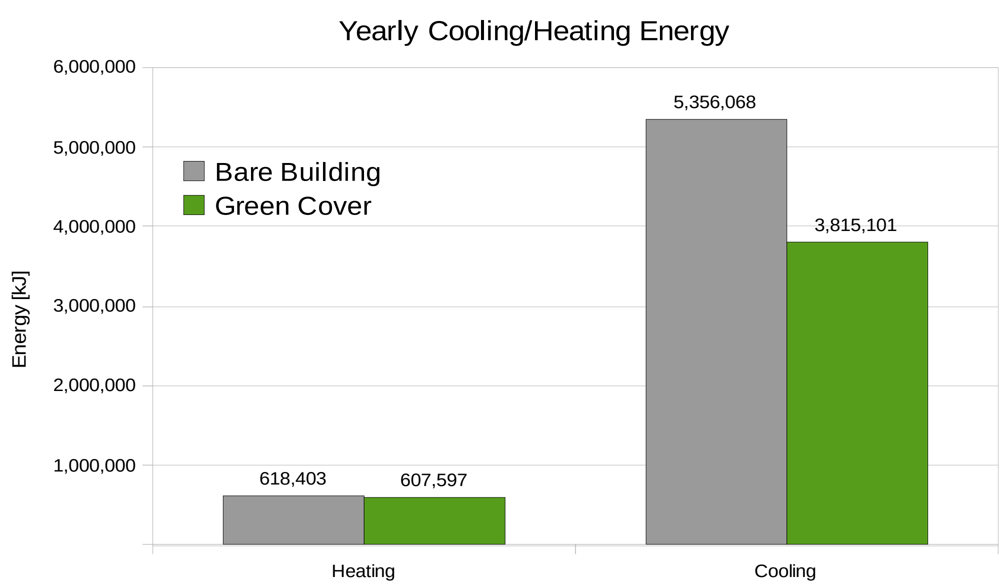

Figure 7.1: Yearly cooling and heating energy of bare building vs. building covered with living walls and a green roof in Tel-Aviv

The results of the Brisbane weather simulations display the same pattern, though the energy savings were less substantial: Significantly more cooling energy was required to cool a bare building over a year-long period (3,895,287 kJ) than was needed to cool the same building with a green roof and living wall covers (3,204,757 kJ). Similarly, the amount of energy required to heat the bare building yearly (9,506 kJ) was greater than the amount required to heat the building covered with a green roof and living walls (5089 kJ).

Table 7.2 presents this set of results. They show that most of the energy required to maintain thermal comfort during daytime hours was cooling energy. In this scenario, the vegetation saved 690,530 kilojoules per year for cooling and only 4,417 kilojoules per year for heating. Figure 7.2 visually demonstrates how relatively insignificant both the heating energy consumption and energy savings appear when they are compared to the cooling-related energy consumption levels.

Table 7.2: Yearly heating and cooling energy savings in Brisbane

	Cooling Total [kJ]	Heating Total [kJ]
Bare Building	3,895,287	9,506
Building with Green Roof & Vertical Vegetation	3,204,757	5,089
Energy Savings Compared to Bare Building	690,530	4,417

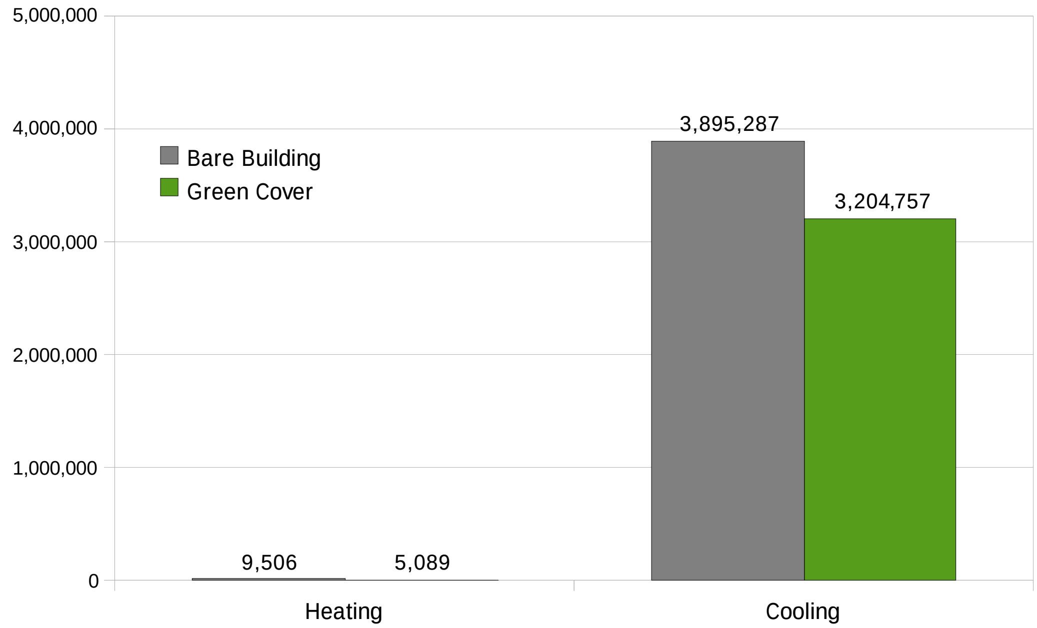

Figure 7.2: Heating and cooling energy for bare building vs. building with green roof and living walls in Brisbane

The results show that cooling energy savings were significant for both Mediterranean Tel-Aviv and for subtropical Brisbane, whereas heating energy savings were negligible. Therefore only cooling energy was considered throughout the rest of the parametric study.

7.2 Equatorial and West Orientations are Optimal for Living Walls

In order to examine the impact of the orientation parameter of the living walls, different simulations of the building were executed with none, one, or more walls of the building covered with living walls. The results were again compared to those of a bare building. In all simulations, the roof was covered with vegetation as well (green roof). The results for Tel Aviv are shown in Table 7.3. They show that adding a polar-facing living wall improved energy savings by only 0.8%; the east-facing wall improved savings by 2.1%; the west-facing wall by 4.2%, and the equatorial-facing wall by 6.8%. The recommended green cover for the building was a combination of a green roof and living walls covering equatorial, west, and east orientations, which produced total energy savings of 27.2%. In summary, if only one living wall were to cover the building in Tel-Aviv, the optimal orientation for it would be equatorial, though the west-facing wall also offers significant energy savings.

Table 7.3: Cooling energy savings of building vegetation cover combinations in Tel-Aviv

Living Wall Aspect	Yearly Savings on Cooling [%]
Roof only	15.5%
Roof + polar wall	16.3%
Roof + east wall	17.6%
Roof + west wall	19.7%
Roof + equatorial wall	22.2%
Roof + equatorial, east, and west walls	27.2%
Roof + all walls	28.8%

In Brisbane, similar results show that the single most effective orientation for a living wall would be the equatorial. Table 7.4 presents full results of the Brisbane subtropical climate study. Although covering the entire wall envelope of the building with vegetation improved energy savings by only 2.4% more than the 15.3% improvement generated by having a green roof alone, covering only the equator-facing wall with a living wall supplied an additional 8.4% in energy savings, totalling 23.7% in savings.

On the other hand, covering only the polar-facing wall reduced the total savings to only 11% and effectively rendered the polar-facing living wall an energy burden. The polar-facing living wall does not convey any cooling benefit, probably because it supplies almost no shading and very little evapotranspiration; It does, however, act as a layer of insulation that decreases the natural cooling of the building overnight. This result differs from the one in Tel-Aviv, probably because overnight ventilation is not significant on hot days given that temperatures fluctuate less between day and night in Tel-Aviv during summer.

Table 7.4: Cooling energy savings of building green cover combinations in Brisbane

Living Wall Aspect	Yearly Savings on Cooling [%]
Roof + polar wall	11.0%
Roof only	15.3%
Roof + east wall	17.1%
Roof + all walls	17.7%
Roof + west wall	19.0%
Roof + equatorial wall	23.7%
Roof + equatorial and east walls	24.5%
Roof + equatorial and west walls	25.1%

The best cooling energy configuration for the building was having a green roof and living walls covering the equatorial and west aspects of the building, a configuration that generated total energy savings of 25.1%. In summary, if only one living wall were to cover the building in Tel-Aviv or Brisbane, its optimal orientation would be equatorial, and the second-best option would be a western orientation.

7.3 Optimal Vegetation Characteristics for Energy Savings

Some parameters of the vegetation itself were found to reduce energy consumption significantly. The most important of these was LAI (Leaf Area Index, which indirectly measures the size of the plant as well as the relative size of its leaves. See Figures 7.3 & 7.4). Using small values for LAI (i.e., LAI=2 or less), it was shown that living walls with tiny leafed plants or no plants at all caused warming and therefore required even more cooling energy than the bare building scenario (microphyll plant species are less able to shed heat). This finding stressed the importance of the living wall not just as an additional layer of insulating mass, but also as an *active* vegetation layer that allowed evapotranspiration processes to occur. The optimal LAI values tested were 4 or 5, but even LAI=3 created a significant energy savings impact for both Tel-Aviv and Brisbane. In Tel-Aviv, even an LAI of 2 increased cooling energy savings, as opposed to Brisbane where the same LAI value did not.

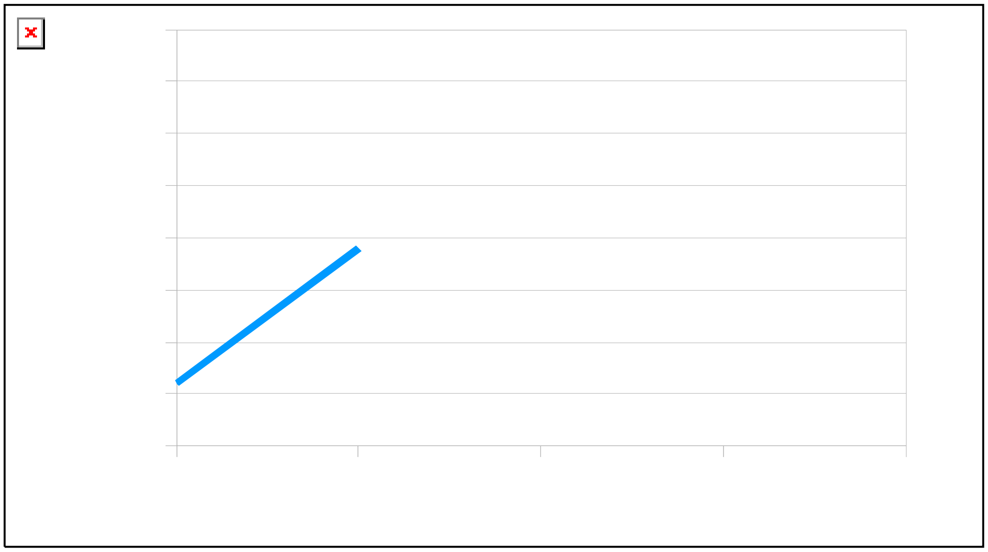

Figure 7.3: Cooling energy savings vs. LAI in Tel-Aviv

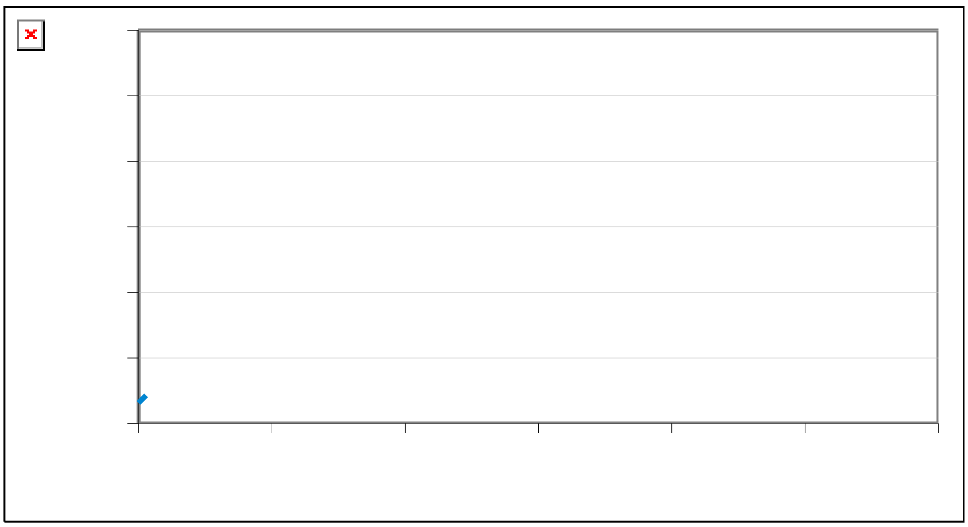

Figure 7.4: Cooling energy savings vs. LAI in Brisbane

To place the LAI values of edible plants in the context of this research, LAI values between 1 and 5 were compared to that of common vegetables. Vegetables are typically grown in cycles measured by days after emergence. At the beginning of the cycle, the plant is young and the LAI is close to 0. As the plant grows, the LAI increases, in some cases reaching values greater than 5. Therefore, to maintain an average LAI of at least 3 for an edible living wall, the planting plan should combine young and adult vegetable plants and/or small varieties with larger ones to achieve optimal plant heights. Further implications of LAI requirements are discussed in Chapter 8.

Another vegetation parameter that influenced the living wall's cooling effectiveness was plant height. Increasing vegetation height improved energy savings in small linear steps, as can be seen in Figures 7.5 and 7.6. When considering plant characteristics for food-producing living walls, the baseline value of a 0.3 metre plant height cannot be taken for granted. Many vegetables grow in short cycles of 40 to 120 days, during which the plant starts from zero height and reaches its full height. Therefore mixing young plants with adult plants, or small varieties with larger ones, should be practiced in order to achieve desired plant height. Further implications of plant height requirements are also discussed in Chapter 8.

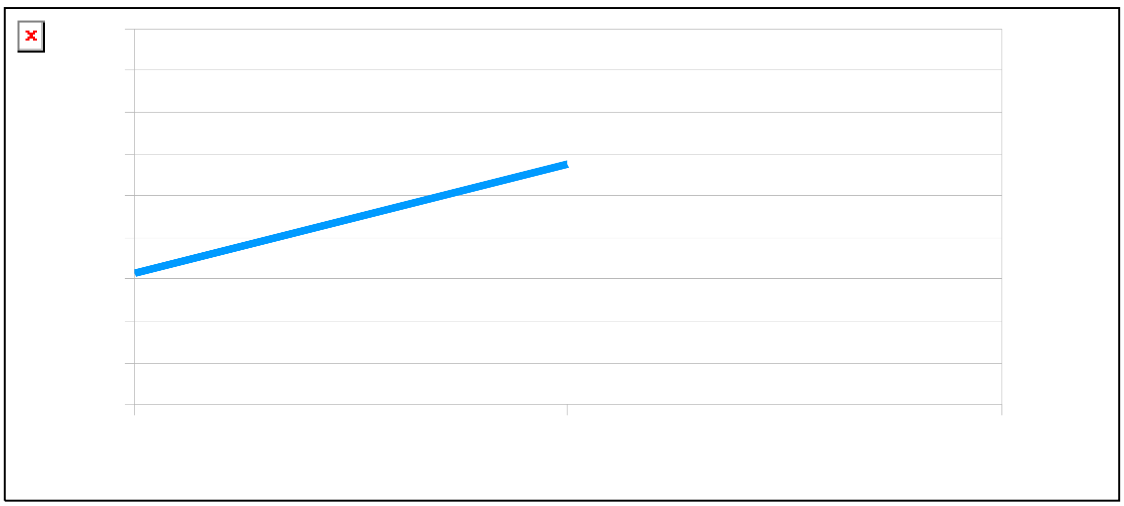

Figure 7.5: Cooling energy savings vs. vegetation height in Tel-Aviv

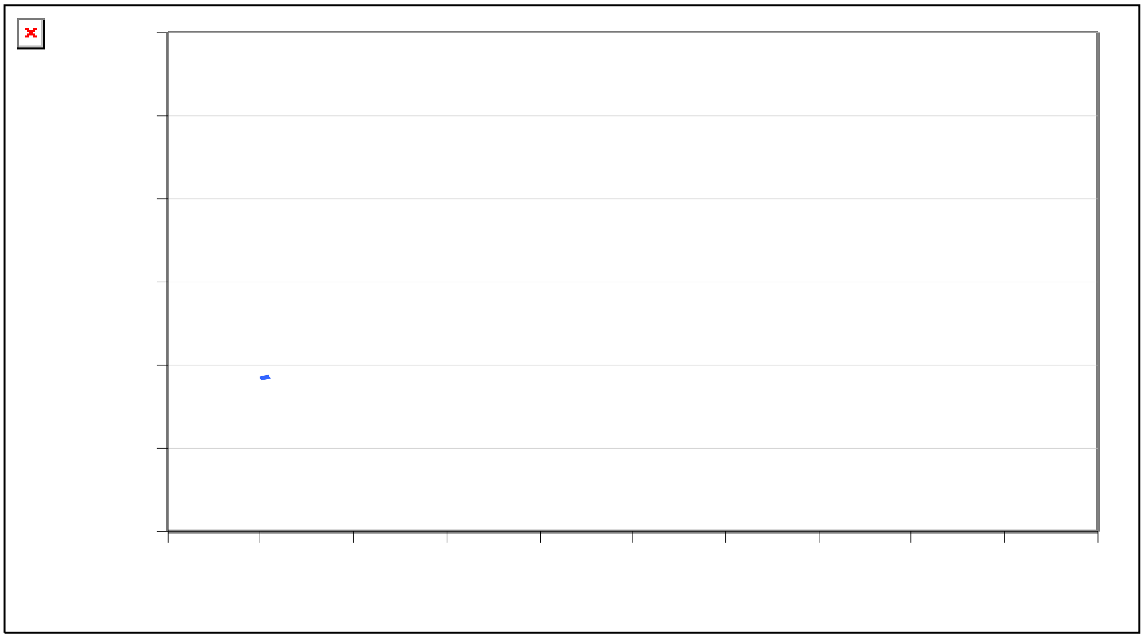

Figure 7.6: Cooling energy savings vs. vegetation height in Brisbane

Other vegetation parameters that influenced living walls' cooling effectiveness in both Tel-Aviv and Brisbane include the following:

- Minimum stomatal resistance (MSR) indicates the leaves' stomatal behaviour with regard to water evaporation. Minimal and maximal MSR values ranging from 50 to 300 resulted in energy savings range of 15% to 22% in Brisbane.
- Leaf reflectivity increases resulted in linear increases in cooling savings ranging from 11% to 22% in Brisbane.
- Leaf emissivity increases resulted in increased cooling savings that ranged from 15% to 19% in Brisbane.

In summary, minimum stomatal resistance, leaf reflectivity, and leaf emissivity of the vegetation were found to have a linear effect on energy savings, whereas vegetation LAI and height dramatically influenced thermal energy savings in both Tel-Aviv and Brisbane.

7.4 *Growing Substrate Characteristics for Optimal Energy Savings*

Changing the parameters that characterise the growing substrate influenced energy consumption for both heating and cooling. The most significant parameters were growing substrate thickness and growing substrate heat conductivity. Growing substrate thickness was a significant parameter for both heating and cooling, indicating that the substrate served as an insulation layer. When set to 6 centimetres thick, living walls reduced cooling energy in Tel-Aviv by 20% yearly, and when set to 14 centimetres, they saved 43% of the cooling energy (Figure 7.7).

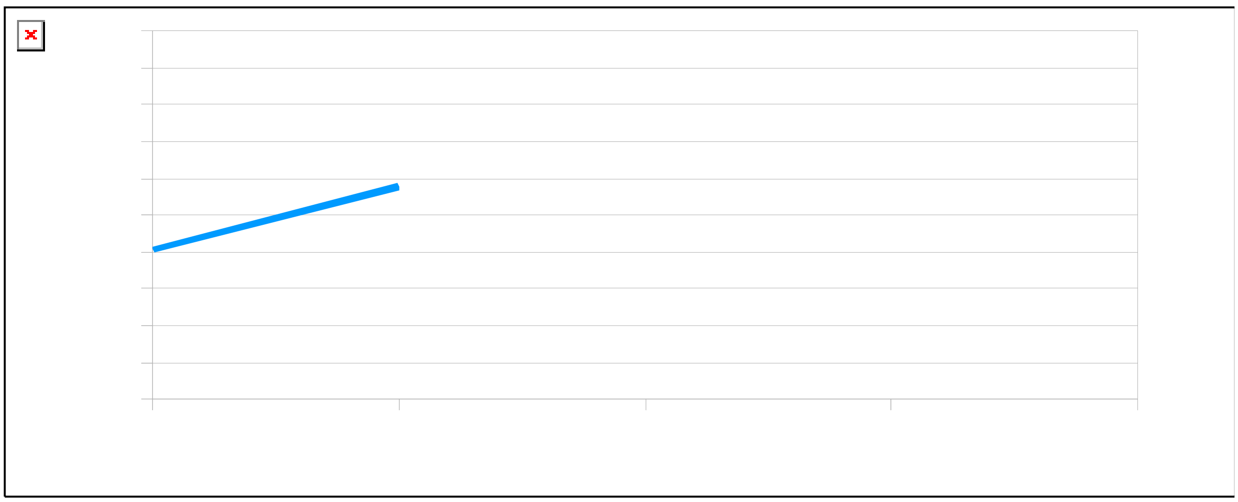

Figure 7.7: Cooling energy savings vs. growing substrate thickness in Tel-Aviv

In Brisbane, a change of a couple of centimetres in growing substrate thickness (from 6 to 8 cm) generated dramatic energy savings changes of from 2% to 18%. Figure 7.8 shows the substantial correlation between growing substrate thickness and cooling energy savings in Brisbane.

Another notable parameter related to growing substrate selection is the growing substrate's solar absorbance: Living walls using growing substrate with solar absorbance of 0.4 resulted cooling energy savings of 35%, while increasing solar absorbance to 0.9 decreased savings by 22% (to only 13%, see Figure 7.9). This indicates that the growing substrate itself received solar radiation that heated it, even though some of the sun was filtered by the plant leaves.

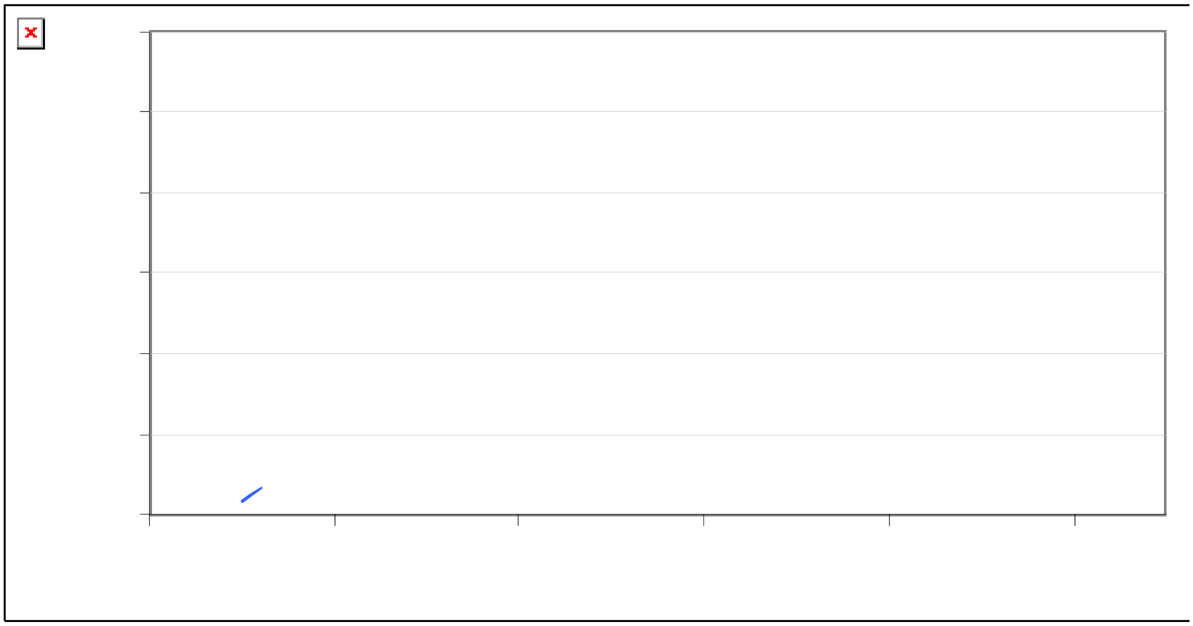

Figure 7.8: Cooling energy savings vs. growing substrate thickness in Brisbane

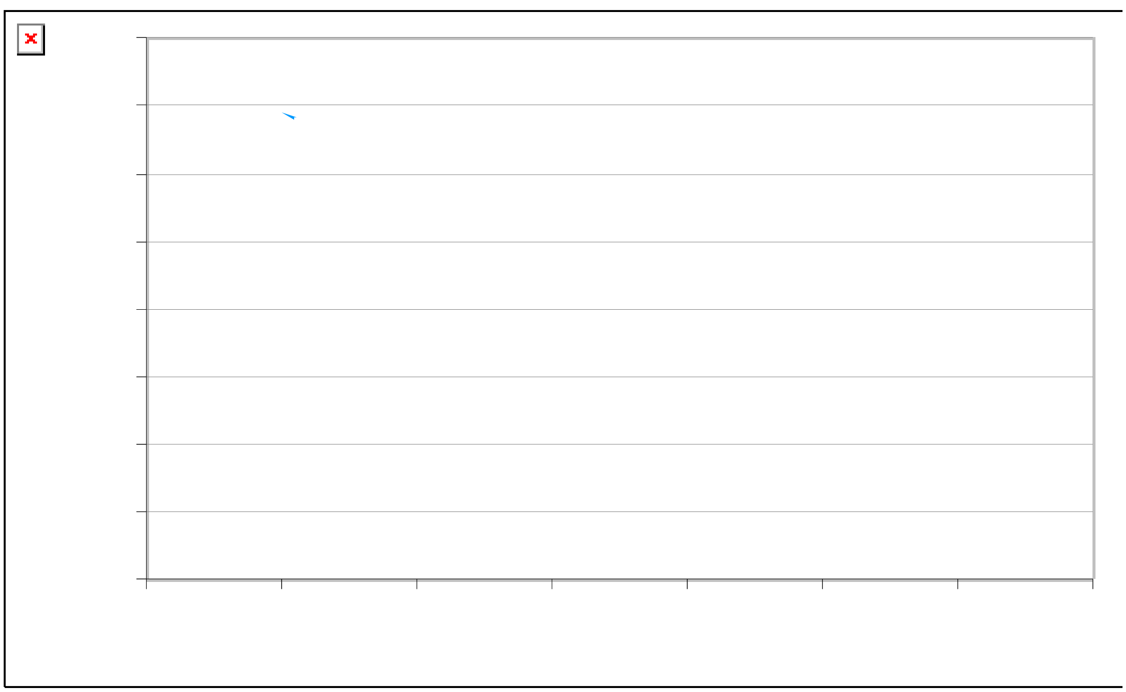

Figure 7.9: Cooling energy savings vs. growing substrate solar absorbance in Brisbane

The growing substrate conductivity parameter was also found to have a major influence on the living wall's thermal performance. Figure 7.10 shows that a slight increase in the dry growing substrate's conductivity can reduce the energy savings dramatically. It is therefore recommended that materials with low conductivity be chosen (preferably lower than 0.4 W/m-k, which was the baseline value).

Other growing substrate parameters such as substrate density, substrate thermal absorbance, residual volumetric moisture content of the substrate, and the specific heat of dry substrate were studied, and all resulted in having some influence on cooling energy, though not a significant one. The parameter of saturation volumetric moisture content of growing substrate is presented in the next section that focuses on irrigation.

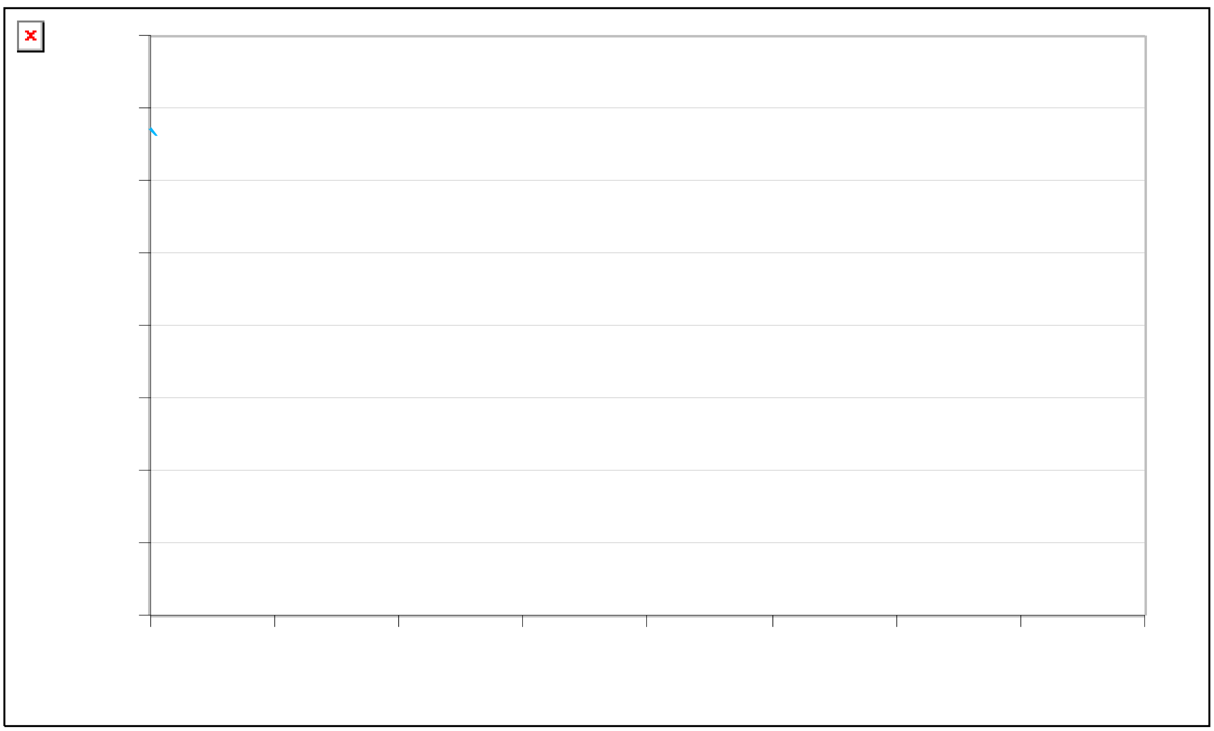

Figure 7.10: Cooling energy savings vs. conductivity of dry substrate in Brisbane

7.5 *Irrigation's Influence on the Cooling Capacity of Living Walls*

Most parameters related to irrigation and moisture significantly changed the living wall’s capacity to cool the building. Higher water retention by the growing substrate improved cooling, indicating the significant influence the growing substrate’s evaporation rate had on the living wall’s ability to create a cooling effect (Figure 7.11).

Sufficient irrigation was also an important parameter for the cooling effect. If irrigation levels were inadequate, then the living wall will instead required more energy to cool the building. If irrigation was reasonable (around 1 millimetres per hour for 2 hours a day in the case of this simulation), the living wall reduced energy consumption levels, whereas if the amount was higher than two millimetres per hour and kept the growing medium and vegetation moist, the cooling energy reduction could go as high as 20% in Brisbane (see Figure 7.12).

These results indicate that the living wall system’s irrigation and moisture levels were very important for cooling, probably due to evaporation and transpiration processes.

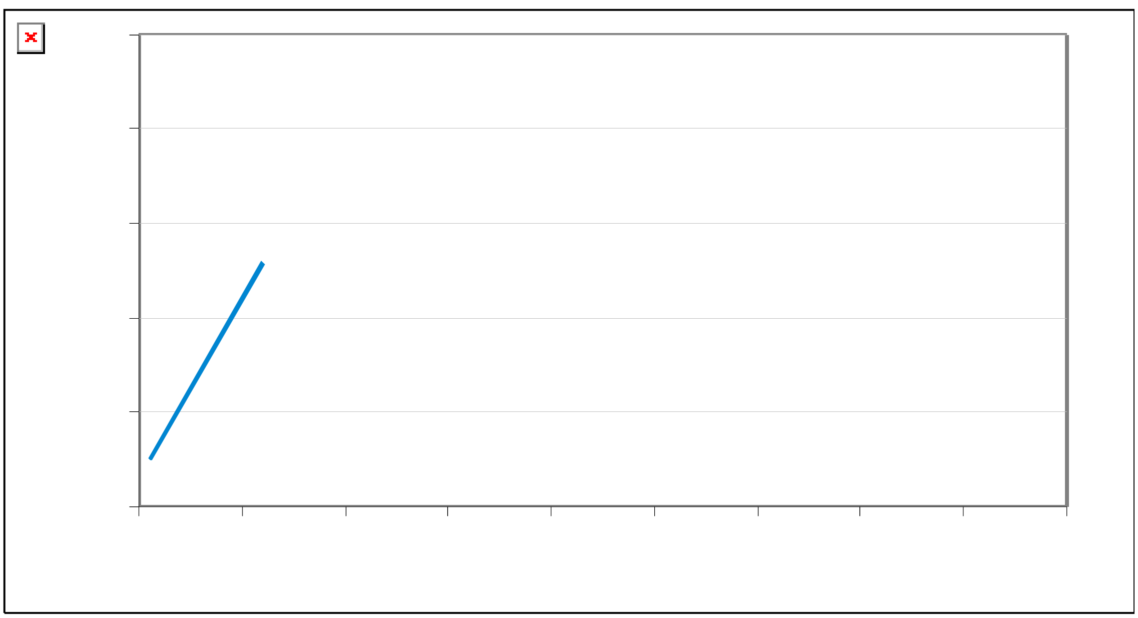

Figure 7.11: Cooling energy savings vs. saturation moisture content of growing substrate in Brisbane

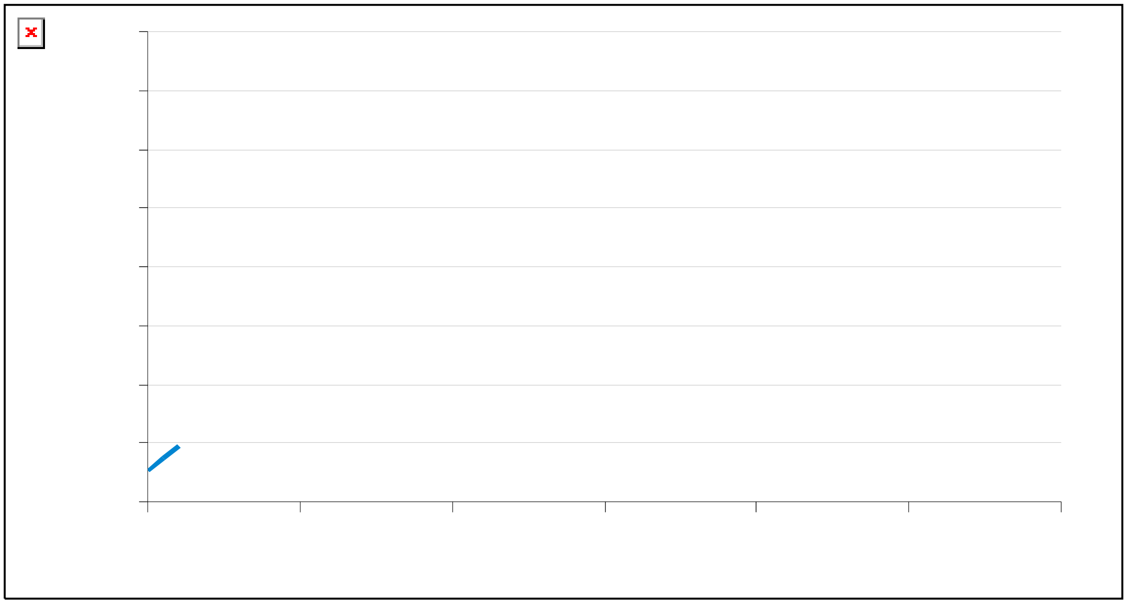

Figure 7.12: Cooling energy savings vs. irrigation in Brisbane

7.6 Summary of Simulation Results

The simulations using the baseline scenario demonstrated that living walls could significantly reduce annual building cooling energy requirements in both Tel-Aviv and Brisbane (by 28.8% and 16% respectively). Because only negligible heating energy savings were demonstrated in both climates, further analysis focused on the reduction of cooling energy requirements that living walls in Tel-Aviv and Brisbane might generate.

In both cases, the most significant living wall orientation was equatorial, though a western orientation was also highly beneficial. The polar-facing living wall made only a small contribution to cooling energy savings in Tel-Aviv, and it actually used more cooling energy than it saved in Brisbane.

According to the results, the design of the growing substrate could be a significant factor in controlling the energy consumption required for cooling the building. The most influential parameters of the growing substrate were its thickness, its solar absorbance, and its capacity to hold moisture. Irrigation was another key factor in the living walls' cooling capacity, as was the choice of vegetation, primarily its LAI.

The results showed that living walls could save a substantial amount of the energy used to cool buildings in some scenarios. On the other hand, they also showed that living walls might, in other cases, increase the amount of cooling energy required. The fact that they were occasionally a thermal burden (depending on their design) demonstrates the impact that design decisions have on living walls that are constructed specifically to save building thermal energy.

8 Synthesis of Living Wall Dynamics

This chapter synthesises the results of the three studies and combines them with existing knowledge to address the research questions presented at the outset of this work. Section 8.1 integrates the knowledge that supports design decisions for improving each of the living wall performance aspects, while Section 8.2 discusses the process of balancing design decisions to optimise several performance aspects.

8.1 Design Decisions for Improving Living Walls' Performance

The following sections review the environmental and social performance parameters of living walls that were addressed in this work. For each parameter, the relevant design decisions identified by the results of the three studies are reviewed and then compared to existing knowledge.

8.1.1 Saving energy with living walls

Existing literature shows that living walls can potentially lower the temperature of building facades in warm climates, thereby decreasing the amount of energy required to cool buildings (Eumorfopoulou & Kontoleon, 2009; Koyama, Yoshinaga, Hayashi, Maeda, & Yamauchi, 2013; Perini, Ottele, Fraaij, Haas, & Raiteri, 2011; Wong, Tan, Chen, et al., 2010; Wong et al., 2009). The results of this research's simulation study support the potential of living walls to reduce building cooling energy requirements significantly. The simulation study demonstrates that the following living wall design parameters influence cooling energy savings:

- living wall orientation and dimensions;
- plant health, density, and size; and
- growing substrate materials and thickness.

Living wall orientation and dimensions

A living wall's orientation has a pronounced influence on its exposure to the sun and other elements. According to previous simulations carried out in the Greek Mediterranean climate (Kontoleon & Eumorfopoulou, 2010), the living wall's ability to reduce indoor temperature was more substantial when it covered west- or east-facing walls: a west-facing living wall achieved 20.8% daily cooling load savings; an east-facing living wall achieved 18.17%; an equator-facing living wall achieved only 7.6%; and a polar-facing living wall achieved even lower cooling savings. This set of findings by Kontoleon et al. was supported by this research.

The main difference in results between the present work and the Kontoleon study concerns the equator-facing wall (which found only a 7.6% savings). The present work determined that the equator-facing wall generated the most significant cooling energy savings in a Mediterranean climate (22.2% savings), and the west- and east-facing walls were next in significance (17.6% and 19.7% savings respectively). This discrepancy in findings regarding equator-facing walls' ability to cool a building can be attributed to differences in both the simulation model and in the structure of the walls.

- In Kontoleon et al.'s study, the walls were constructed of layers of masonry and insulation, and they did not have any windows or doors. This work's simulations included a window and a door, and the walls were constructed of wood, fibreglass, and plasterboard.
- The energy savings in the Kontoleon study were calculated as the daily energy load on a warm summer day, and when the sun is closer to its zenith, the amount of sunlight striking the equator-facing wall is reduced. This work's results calculated year-long cooling effects and thus incorporated seasons in which the sun is lower and strikes the equator-facing wall for longer periods.
- The meteorological data used for the Kontoleon study originated from Thessaloniki in the northern part of Greece. The latitude there is 40°38'N, as opposed to Tel-Aviv's, which is 32°4'N, a distinction significant enough to reflect a difference in climate.

In summary, both studies suggested that the living wall's orientation influences building cooling energy requirements considerably. A polar-facing living wall is probably an inefficient cooling energy saver, whereas west and east orientations may have a significant building cooling effect. The significance of the equator-facing façade was supported by an experiment with green facades in Mediterranean climate (Pérez, Rincón, Vila, González, & Cabeza, 2011). Therefore the equator-facing wall may have the most significant effect when considering cooling energy savings for the entire year in warm climates.

Plant height and LAI

A simulation study in Singapore's tropical climate (Wong et al., 2009) showed that vegetation's LAI was highly correlated with the shading coefficient of the vegetation (see Figure 8.1), meaning that larger LAIs are expected to influence cooling energy savings positively. However, the Wong simulation study did not take evapotranspiration processes into account, nor did it simulate cooling energy consumption. The actual impact of the LAI parameter is thus expected to be more significant, as was indeed one of the findings generated by this work's thermal simulation study. No other studies of living walls were found that accounted for the impact of plant height and LAI.

In addition to the LAI parameter, the thermal simulation study found that the height of the vegetation also influenced the building's thermal performance significantly. The findings of this work can be encapsulated to a recommendation to use vegetation with an LAI above 3 and a height of more than 10 centimetres in order to supply significant building energy cooling savings in both Brisbane and Tel-Aviv climates. These results add to existing knowledge by supplying parameterised detail to the general recommendation of simply using dense vegetation.

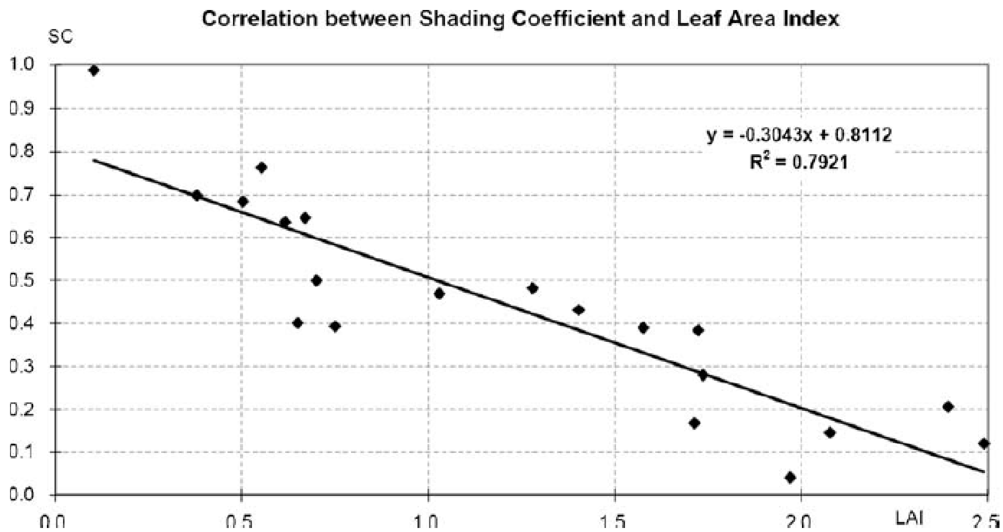

Figure 8.1: Correlation between shading coefficient and LAI according to Wong et al. (2009)

Growing substrate materials and thickness

Another study of vertical greenery systems' thermal properties in Singapore (Wong, Tan, Chen, et al., 2010) found that the most effective living wall systems for lowering surface temperatures were generally those with a thicker substrate (23–28 cm). Most of the effective systems also incorporated a thick layer of vegetation (10–20 cm). That study determined that the least effective living wall system for lowering surface temperature was a climber system with no substrate layer. In that sense, the results of Wong et al.'s 2010 study are similar to the results of this work in stressing the important effect that a thick substrate layer has on living walls' thermal properties, as well as that stemming from a thick vegetation layer (noted as large vegetation height in this work).

One result that stood out in the study of Wong et el. was a specific living wall system (noted therein as VGS4) that incorporated a relatively thin substrate layer (8 cm) with thick vegetation (12 cm) and yet, surprisingly, resulted in significant temperature reductions. This can be explained by differences in substrate type and content moisture, as well as differences in vegetation coverage. Nevertheless, this result complements the findings of the thermal simulation in this work that recommend a substrate thickness of at least eight centimetres. Wong et al.’s research did not analyse design differences between the living wall systems generally, focusing instead on the overall potential of living walls to reduce urban heat islands and save buildings’ cooling energy.

Other parameters that influence thermal performance

In a study of green facades (climbers on walls) and the key plant traits that contribute to their cooling effects in Japan, it was found that the amount of coverage was the main parameter influencing green facades’ overall cooling effect (Koyama et al., 2013). That study also found a negative relationship between leaf solar transmittance (how much sunlight the leaves let through) and the net cooling effect. Both of these results from the Koyama et al. study support the results of this work.

This work’s simulation study demonstrated the effectiveness of an additional influential parameter. Moisture, which is related to evapotranspiration processes, was a crucial factor affecting the success of the living wall as a building cooling aid. This parameter was not specifically studied previously, probably owing to the difficulty in simulating evapotranspiration.

To summarise this segment, then, the design properties that were found to have a significant positive impact on the living wall's ability to save building cooling energy were large dimensions, coverage of equatorial, west and east facades; thick (>8 cm) growing substrate layers with high moisture content; tall, dense vegetation (LAI>3, height>10 cm), and irrigation that supplies enough moisture for both the vegetation and the substrate. These findings add new, specific information to our knowledge of living walls’ design parameters and their values.

8.1.2 Food production with living walls

The results of the edible living walls study in this work showed that the productivity of living walls varied between the living wall systems, and that it was influenced by the following traits:

1. available volume for roots,
2. planting angle,
3. plant selection, and
4. spacing between plants.

In addition, it was assumed in this work that edible living walls had full sun exposure (at least 6 hours per day), and received proper irrigation. Each of the above design parameters is discussed in the next sections. The findings are then compared to existing knowledge.

Available volume for roots

The results of the edible living wall study showed that living wall systems with larger available root volume produced greater yields. Only leaf vegetables were able to produce yield when planted in volumes of less than one litre per plant. It was also noted that volumes of six to eight litres per plant were sufficient for growing most vegetable types. However, the quantitative influence of substrate volume on vegetable yields should be discussed in order to better inform design decisions related to this parameter.

Although there were only four data points (i.e., 4 living wall systems) marking the influence substrate volume had on yields, the trend was clear; Results showed that the relationship was approximately linear (see Figure 8.2). For example, when comparing the system with 52 litres per square metre to the one with a volume of 100 litres per square metre, the monthly yield is nearly four times smaller in weight (232 gr compared to 905 gr).

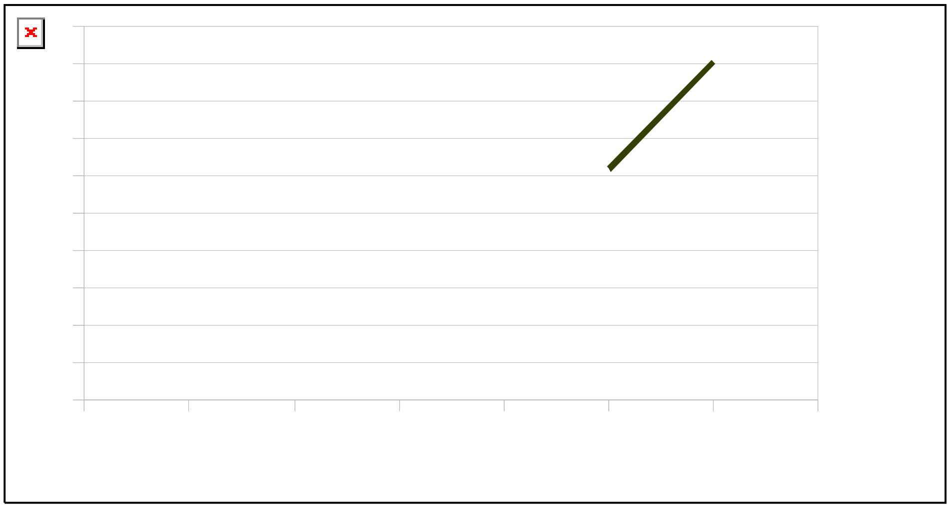

Figure 8.2: Growing substrate volume per vertical area and monthly harvest weight per area for four productive living wall systems

The assumption is that the limited growth of plants in the systems with smaller amounts of substrate is associated with their root system volume. The influence of root restriction on the development of plants (and specifically on vegetable productivity) is documented in many studies. According to NeSmith and Duval (1998), increased biomass of the top part of the plant is linearly correlated with increasing growing substrate volume for many agricultural crops. Nishizawa and Saito (1998) found that tomato plants grown in 0.4-litre containers were 60 precent shorter than those grown in 7-litre containers. Previous studies (Bar-Tal & Pressman, 1996) also demonstrated that root restriction of greenhouse tomatoes reduced total productivity, decreasing yields from 7.7 kilograms per plant to 6.3 kilograms per plant on average. The influence root restriction had on the yield of greenhouse tomatoes was mild when compared to that recorded by this work. This discrepancy can be explained by two factors. First, the Bar-Tal and Pressman study did not provide information regarding the volume of restricted and non-restricted roots, and secondly, the tomatoes were grown aeroponically, thus their root restriction cannot be reliably compared to root-restricted tomatoes grown in soil-based substrate.

The general trend established by agronomic research, that limiting vegetables' root volume reduces their yield, was confirmed by the results of this work, though the extent of this limitation was found to be more pronounced. The first possible explanation is that the food production study reflects domestic growing conditions, whereas the extant literature is based on studies carried out in agriculture research facilities, where plant conditions (such as fertilisation) are optimised and may thus compensate for lack of root space. It was also shown that container geometry and substrate selection have a pronounced effect on soil moisture content and aeration (NeSmith & Duval, 1998) and thereby influences growth rates in container-grown plants. Because the variety of growing substrate types, aeration levels, and actual moisture content were not studied in this work, more research is needed to further inform substrate selection.

In summary, a larger volume of substrate is preferred for edible living walls, but additional parameters (e.g., substrate type) are also involved, and more data is required to fully understand the quantitative relationship between substrate volume and yields for food producing living walls.

Planting angle

The results of the edible living wall study showed that a non-horizontal planting angle does not allow vegetables to be raised from seed, and therefore requires seedling transplants. Transplanting root crops such as beets and carrots is not recommended, however, since it "generally causes root deformation and undesirable lateral root development." (Schrader, 2000). Accordingly, in the edible living wall study, root vegetables were grown from seed only in living wall systems with a horizontal or near-horizontal planting angle. The planting angle parameter may thus restrict the selection of vegetables.

Apart from the above observation, this work found the planting angle to be an insignificant factor in the suitability of the living wall for food production. The most productive living wall system in terms of harvest weight per vertical area had a 70º planting angle, and the second-most productive system had a horizontal planting angle. Because no previous studies considered a variety of living walls for food production, this particular result cannot be compared to others.

Plant selection

Having now discussed the issues of available root volume and planting angle, it should be noted that these design parameters interact with plant selection. Decisions made regarding one parameter affect the other parameters, and thus plant size should fit the living wall's planting angle and the available root volume if it is expected to successfully produce food.

According to the results of the survey in this work, living walls planted with perennials were considered to be less successful food producers. However, the effective growth of perennial herbs, specifically "mint, rosemary, thyme, tarragon, chives and oregano," in living walls has been documented in Australia (Loh, 2008). Additionally, the edible living walls study in this work resulted in perennial herbs being grown successfully in most of the living wall systems tested, although they did not constitute a large percentage of the total yield for any of the systems, due to their relatively low weight.

Regarding the choice of perennials for an edible living wall, the structure of the questionnaire can explain the mismatch between the results of the survey, on the one hand, and the results of the edible living wall study and those reported in the literature, on the other. Although the question about the type of plants was multiple choice where more than one option could be chosen, it is possible that participants chose 'herbs and medicinals' rather than 'perennials' because the latter is less specific than 'herbs'. Thus it was concluded that both perennials and annuals are good choices for food producing living walls. In addition, the edible living wall study showed that planting a variety of vegetable types and species (i.e., heteroculture) was successful and may contribute to better usage of the growing space and greater harvest diversity for the living wall user. The literature also noted that heteroculture improves pest resistance (see Section 4.2.4). However, neither this nor any previous study specifically compared the yields of heterocultural versus monocultural living walls.

Spacing between plants

Interestingly, very few adverse effects became apparent from increasing the density of plants during the edible wall study portion of this work. In fact, it usually resulted in improved yield per vertical square metre. However, agricultural scientists have established equations to depict the relationship between yield and density (Holliday, 1960), and according to these, yield increases with density until it reaches a maximum density per area. Bulson, Snaydon, and Stopes (1997) noted the recommended density (RD) proposed by agronomic studies for each crop type. Although this study may seem to suggest that higher densities result in higher yields per area, it is probably safe to assume (in the absence of precise quantitative data) that the RD values recommended in literature for each crop should be adhered to unless the physical design of the living wall system prevents it. The RD values are valid for monocultural agriculture, while heteroculture gardening make it more difficult to define and decide upon the recommended density for each plant.

Crop yield of edible living walls

The productivity of living walls was not addressed in the existing literature. Related topics that did receive some academic attention were green roofs for urban agriculture and vertical urban farms (see literature review for more details), but no information regarding their yield was available. Fortunately, data regarding average productivity levels of organic agriculture in Israel has been recorded, and that data offers a valid basis for comparison with the productivity-related results of the living wall studies carried out in Tel-Aviv over the course of this work. The monthly harvest of living wall systems examined by this work was 0.2 to 0.9 kilograms per square metre (depending on the living wall system), and the yearly harvest was 2.4 to 10.8 kilograms per square metre.

Statistical agricultural data state that organic vegetable crops were grown on 52 thousand dunams (dunam = 1000m^2) and yielded 64.5 thousand tons (Central Bureau of Statistics, 2014) in Israel in 2012. This translates to an average yield of 1.24 kilograms per square metre, a figure which includes the following crops: carrot, celery, tomato, zucchini, cucumber, pumpkin, melon, onion, potato, radish, corn, bell pepper, chilli pepper, and sweet potato. With the exception of leaf vegetables and herbs, that data's mix of vegetables is similar to that in this work. The comparison between the yield from a vertical square meter of domestic living walls to the yield of a horizontal square meter of agricultural land shows that all the living walls systems were more productive (2.4–10.8 kg compared to 1.24 kg/m^2). This difference can be explained by the intensive maintenance of the domestic living walls, the use of polyculture, and the higher planting density. Irrigation is another related factor that is discussed in section 8.1.4.

Living wall productivity can also be compared with that of greenhouse agriculture, where space is more expensive and thus creates more need for dense planting and higher frequency maintenance. According to the USDA's "Appropriate Technology Transfer for Rural Areas" information, greenhouse tomatoes and peppers yield two to three pounds per year per square foot (Greer & Diver, 2000). This translates to a yield of ten to fifteen kilograms per square metre, which is ten times higher than the figure for organic field vegetables in Israel. The relatively low productivity range of the edible living walls in this work (2.4–10.8 kg/m^2) compared to the productivity suggested for greenhouse vegetables (10–15 kg/m^2) can be partially explained by the greenhouse's capability to adjust the microclimate to suit the plants and to the protection it offers from pests, but the professional growers' ability to optimise agronomic parameters is probably the principal factor.

In addition to that, the comparison between horizontal area and vertical area is inherently flawed. The vertical area of city walls or fences that can be used for food production is 1.7 square metres for each one-metre-long wall or fence (assuming it covers the height range of 30 to 200 cm). In an urban setting, it could be more reasonable to multiply the results by 1.7, thereby reaching a yearly harvest of 4 to 18 kilograms per one-metre-long vertical surface. This number is comparable to the greenhouse yield values, and it is safe to assume that this number would increase were the edible living walls managed by professional growers.

In summary, the results of this work combined with the research literature indicate that larger root volume improves productivity, that a horizontal planting angle is only important if root vegetables are grown (or if the vegetables are grown from seed), and that crop diversity may be preferable. The productivity of the domestic edible living walls was found to be generally higher than that of organic field gardening but lower than that generated by intensive greenhouse practices.

8.1.3 Lowering the embodied energy of living walls

Good practice of product design and architectural design considers the entire lifecycle of the products used, including materials and manufacturing techniques. According to a 2011 living wall life cycle analysis conducted by Ottele, Perini, Fraaij, Haas and Raiteri (2011) in the Netherlands, the choice of materials was a crucial component in estimating a living wall system's sustainability. Ottele et al.'s study reinforces this research's finding that embodied energy differences between living wall systems can be paramount, concluding that the only sustainable options for living walls in a Mediterranean climate are direct climber vegetation or a living wall based on planter boxes.

The results of this work showed that it is not only possible to use materials that are reused, recycled, and recyclable and to access local sourcing and manufacturing, but that doing so can improve the sustainability of living wall applications. However, for the options analysed in this work, a trade-off emerged between the use of low embodied energy materials (local and reused materials) and the system's life span. Particularly, the reused/recycled options (namely Reclaimed Pallet and Invivo Pocket) had the shortest life span (3 to 6 years) compared to the other systems with at least a fifteen-year life span.

In summary, both the literature and this work agree that alternative living wall systems are a viable option and that the environmental cost of materials, manufacturing, transportation, and maintenance are all highly relevant to designing a living wall that contributes to sustainable urbanism.

8.1.4 Improving water efficiency of living walls

This work indicated that living wall systems consume varying amounts of water to grow vegetables (see Chapter 5). The results were calculated per system and resulted in a range of 21 to 371 litres of water per kilogram of harvest, depending on the living wall system. Those results are presented here in ascending order: Invivo pocket (21 litres/kg), Reclaimed pallets (25 litres/kg), Woolly pocket (162 litres/kg), Aria (229 litres/kg), ELT (243 litres/kg) and Domino planters (371 litres/kg).

For comparison, the water footprint of vegetable crops in traditional agriculture is roughly around 300 litres per kilogram (Mekonnen, 2010). This water footprint includes blue, green, and grey water, which means that it includes all water that evaporated during the growth of the crop (blue), the (green) rainwater, as well as the (grey) water required to assimilate the pollutants (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2009). Since the amount of irrigation was measured in the edible living wall study, it would be more accurate to compare the irrigation amount with the blue water footprint alone. Recent calculations of worldwide data showed the following blue water footprints for vegetables that were also grown in the edible living wall study (Mekonnen, 2010): brassicas (181 litres/kg), tomatoes (108 litres/kg), eggplants (234 litres/kg), beans (320 litres/kg), lettuce (133 litres/kg), and peppers (240 litres/kg). In short, the expected blue water footprint for the types of vegetables grown in the living walls would be around 150 to 200 litres per kilogram.

The comparatively low water consumption of some of the edible living wall systems can be attributed to the fact that those vegetables were grown in containers, whereas moisture is easily lost to the ground below the plant roots in traditional agriculture. Mekonnen noted that irrigated agricultural crops have a lower consumptive water footprint than do rain-fed agricultural crops (2010), a factor that helps explain the relatively low water consumption of the living walls.

Nonetheless, the results of this work regarding water consumption were focused only on edible domestic living walls. When the broader options of living wall vegetation types (e.g., drought resistant plants or tropical plants) are considered, the water consumption values of living walls are expected to exhibit even greater variability. Moreover, there are living wall systems—mostly hydroponic living walls—that recycle the water used, making them extremely water efficient. In addition, this work did not examine the option of watering living walls with collected rainwater or grey water as a way to decrease potable water consumption (Loh, 2008).

Looking again at green roofs, it is claimed that they have a part to play in sustainable water management and supplying hydrological benefits, specifically modulating runoff and improving runoff quality (Dunnett & Kingsbury, 2008). It is expected that living walls can supply similar benefits, although the extent and specifics of these benefits in the context of living walls (where runoff percolates through layers of vertical substrate and vegetation) are yet to be researched.

In summary, the water efficiency of edible living walls was characterised by high variability between different living wall systems. Most domestic living wall systems were more water efficient than traditional agriculture. Additional hydrological aspects of living walls, specifically the hydrological benefits of improving water quality and moderating runoff, should be further researched.

8.1.5 Enriching biodiversity and urban ecology with living walls

Because biodiversity enrichment was addressed only in the survey study portion of this work, related results are very limited. According to the living wall users survey, the average rating of living walls as biodiversity enhancers was low (<3), which means that their users did not generally perceive living walls as having a large biodiversity benefit. In addition, exterior living walls were rated higher as biodiversity enhancers.

These results somewhat contradict existing literature that suggests that green roofs and living walls have the potential to support life in an urban context. Green facades were specifically noted for their ability to provide roosting and nesting space for birds (Chiquet et al., 2012; Kohler, 1993; van Bohemen et al., 2008), hibernation opportunities for insects, as well as nectar and fruit for birds and insects (Dunnett & Kingsbury, 2008). In terms of the design of the living walls, there are principles used when designing habitat gardens that can be applied to living walls. These include favouring local plants, managing pests and weeds naturally, as well as providing food, water, refuge, and nesting sites to birds, mammals, invertebrates, and amphibians (Grant, 2003).

One of the design parameters for the creation of green roofs for biodiversity in Basel, Switzerland, is that the growing substrate should be based on natural topsoil from the surrounding area. Such green roofs are claimed to be suitable for locally and regionally endangered species (Brenneisen, 2006). This principle can also be applied to living walls, although it has not yet been established by existing research.

In summary, some living walls design decisions can promote the living walls' ability to enhance biodiversity and ecology, although only a few green facades were shown to have such impacts. However, these results did not carry over to the living wall users who participated in the survey.

8.1.6 Enhancing psychological benefits of living walls

The literature suggests that the existence of greenery in the city "may have a considerable potential for improving the health of urban residents" (Tzoulas et al., 2007, p. 171). More specifically, natural features such as living walls may contribute to psychological well-being, personal fulfilment, longevity, relaxation, increased positive self-reported emotions, and lessened aggression (see Section 2.1.8). Living walls are therefore assumed to be a generally preferred view, especially in the city.

The results of the survey in this work reinforce that assumption: The average perceived success of the living walls (rating the living wall as 'overall successful') was 4.14 (on a scale of 1–5). In addition, the performance of living walls as 'relaxing and mood improving' was by far the most highly rated response (4.32 on a scale of 1–5). These results show that living wall users who participated in the survey were generally highly satisfied with their living walls, and they regarded them as significantly relaxing and mood improving.

In a survey intended to study the perception of vertical greenery systems in Singapore, the participants (building occupants and building professionals) agreed to most of the suggested benefits of living walls (Wong, Tan, Tan, Sia, & Wong, 2010). These included thermal and psychological benefits and biodiversity enhancement. These survey results are similar to those generated by the survey in this work (i.e., the overall perception of living walls was positive). However, the results of Wong et al.'s 2010 study are not comparable to the results of the parametric study presented in this work. First, the 2010 research targeted professionals as well as residents, and it also did not consider the design of the living walls. This work targeted users of specific living wall projects, which facilitated questions about location, irrigation, vegetation choice, maintenance, and other design parameters.

The current work highlighted one design parameter that appears to influence living walls' psychological benefits. Large living walls were rated significantly higher than small living walls, both in the 'overall successful' and in the 'relaxing and mood improving' parameters (see Table 8.1). The size of the living wall was therefore found to be a critical factor in its ability to confer psychological benefits.

Table 8.1: Rating of large living walls compared to small living walls

	Large Living Walls >5m2	Small Living Walls <5m2	p Value
'Overall Successful'	4.53	4.02	0.007
'Relaxing and mood improving'	4.67	2.22	0.021

In summary, living walls are generally considered to have much potential to provide psychological benefits, and that potential is reinforced by this research. The survey results indicated that living wall users were satisfied with their living walls and considered them to be relaxing and mood improving. This was true overall, and was even more the case for large living walls.

8.1.7 Increasing living walls' educational benefits

On average, the participants of the survey in this work considered their living walls to be educational (average rate of 3.61 on a scale of 1–5), and there was high variability between the respondents (var = 2.03). This variability may be at least partially explained by the inherent variability of the designs. Indeed, some of the living wall design parameters were found to be related to their perceived ability to be educational. This work's survey found that domestic living walls were considered to be less educational (3.31 vs 4.64, $p < 0.001$) and that those located in residential areas were also deemed less educational (3.36 vs 4.62, $p < 0.001$). These results contribute to the notion of the educational living wall as a public attraction, accessible to many. The findings also indicated that the school design scheme (a large, exterior living wall located at a school) was considered significantly more educational than other design schemes. While this result was expected, it can be added to the previous results to inform future designs of educational living walls.

Some books and review papers examining green roofs and living walls generally have noted the educational potential of living walls (Hopkins & Goodwin, 2011). For example, Sheweka and Magdy (2011) mentioned that living walls are perfect tools to teach about the environment. However, no research that specifically studied living walls' suitability as educational tools nor any potential design decisions related to their educational potential could be found.

In summary, living walls are considered to have the potential to be educational and this research reinforces this aspect. Living walls that are either large exterior walls at schools or located at public buildings in a non-residential area are perceived to be more educational.

8.1.8 Strengthening sense of community with living walls

According to the survey conducted in the course of this work, living walls were not necessarily believed to contribute to a sense of community. The average of the responses was 2.91 (which is relatively low), and the participants exhibited much variability (var = 2.37).

Although no available studies of factors contributing to a sense of community related specifically to living walls, a closely related survey noted that natural features "play a particularly important role in sense of community" (Kim & Kaplan, 2004). Tzoulas et al. (2007) developed a conceptual framework connecting green infrastructure with community health (defined as sense of community, community empowerment, social capital, and culture), claiming that "a Green Infrastructure through its ecosystem functions and services creates the environmental settings for community health." (p. 174). It has also been argued that integrating living walls into community gardens or other urban farming operations can potentially make the living wall a centre of community life (Wood et al., 2014). Existing literature generally agrees that living walls have the potential to increase a sense of community, though the results of the survey in this work did not specifically support that contention.

However, the survey did highlight a few design parameters related to sense of community. For example, living walls larger than five square metres were perceived to enhance a sense of community significantly more than did small living walls (3.93 vs 2.61, $p = 0.001$), thus a larger size of the living wall was found to increase the living wall's likelihood of enhancing sense of community. Similar to the findings related to 'educational' performance, domestic living walls and walls in residential areas also received a lower rating along the 'enhancing sense of community' parameter (2.67 vs 4.07, $p > 0.001$; and 2.70 vs 3.77, $p = 0.027$ respectively). Finally, the school design scheme (large exterior living walls at schools), with a high average of 4.71 for this parameter, was perceived to have a markedly greater effect upon community enhancement.

Surprisingly, interior living walls were also perceived to be better community enhancers. Respondents with interior living walls rated their walls as 'enhancing sense of community' higher, on average, than the same rating related to exterior living walls (4.33 vs. 2.78, $p = 0.023$). This result is statistically significant despite there being only six cases of interior living walls represented in the survey.

In summary, according to the survey, living walls' ability to enhance a sense of community is debatable and is related to the living wall's design parameters. Large living walls, whether they be located at schools, at an office, or in public building interiors in a non-residential area, are perceived to enhance the sense of community.

8.1.9 Improving user experience of living walls

In this work, user experience of living walls refers to the experience of a person using the living wall with respect to how easy it is to setup and maintain and how pleasing it is to watch. The results that are related to living walls' user experience were attained during the edible living wall study, wherein the user experience of the various living wall systems was evaluated mainly by the researcher (see Section 4.2.5). The design parameters influencing user experience were porosity of materials, vegetation height and density, growing substrate stability, weight of the substrate, and living wall height.

The edible living wall study portion of this work demonstrated that the choice of living wall system can influence the appearance of the living wall. During that study, the researcher's impression was that most people reacted positively to the sight of healthy, living plants and negatively to visible stains on top of the system (although a few approved of it as a "natural" look). Nevertheless, it is possible to plan the living wall so that plants cover virtually the entire living wall system, thus camouflaging the stains with live vegetation. If designed appropriately, staining will not detract from the wall's appearance.

Plant height and density are both highly important factors affecting individuals' visual landscape preferences (Misgav, 2000). These parameters are related to the landscape's 'naturalness' (Lamb & Purcell, 1990). One would therefore expect the vegetation's height and density to have an impact on the perceived success of the living wall. Validating this assumption requires further research. Essentially, high plant LAI values and larger plant heights offer useful thermal benefits, and the appearance of walls with these features can reasonably be expected to be perceived favourably.

User experience of living walls begins with the ease of initial setup. This work indicated that one of the major factors affecting ease of setup was the weight of the growing substrate. A living wall that must be filled with a large volume of heavy substrate involves a substantial amount of setup work. However, since root space is an important factor affecting the growth of edibles, incorporating the maximum amount of substrate possible within the limits of construction-weight restrictions is recommended for edible living walls. Lightweight growing substrate such as Perlite can allow larger substrate volume when weight is a restricting factor. It also alleviates some of the laborious setup process.

Substrate stability was found to be a significant parameter influencing user experience in this study because the living wall systems were used intensively for seasonal edible plants and required multiple sessions of seeding, planting, and replanting. Some of the living wall systems were not designed for such intensive maintenance or did not readily accommodate other forms of maintenance (e.g., replacing entire modules when plants needed to be replaced). Maintaining living walls with stable growing substrate was easier and therefore preferable.

The last design parameter related to user experience was the living wall's height. This human-factor design parameter can be compared to the location of a writing board. A traditional recommendation for a class chalkboard is that it be positioned at a height of between 100 and 200 centimetres (Kumar, 1996). A more recent recommendation is to use a large board 52 inches (132 cm) high and mount it 34 inches (86 cm) from the floor (Niemeyer, 2002). The workable surface would thus fall within the range of 86 to 218 centimetres, which is higher than the 30 to 200 centimetres recommended by this work's findings. However, a whiteboard's position must offer maximum visibility to students seated throughout the classroom and it must account for teachers' ergonomic considerations. Living walls can be lower because the relevant considerations differ.

In addition, some living wall users might prefer to be seated during some of the maintenance work, and any child-aged users would interact with vegetation at a height of less than 86 centimetres. Indeed, a suggestion for a living wall designed for accessibility by wheelchair users specifies that the living wall height should be between 35 and 135 centimetres (Hopkins & Goodwin, 2011). Therefore the recommended height varies according to the circumstances and functions of the living wall. When ease of use is important, the specific characteristics of the users (such as height and physical ability) should be taken into account when deciding on the height of the living wall.

In summary, living walls' favourable appearance is related to their 'naturalness', which is, in turn, related to high vegetation size, density, and health (LAI and height are reliable indications). This relationship was deduced from previous research that is not specific to living walls, and it was supported by this work. Living walls' favourable appearance may also be related to a lack of visible staining. Other design parameters such as the pattern and colour of the vegetation may be related to favourable appearance, but they require future research. In terms of ease of use, lightweight substrate that is designed to be stable enough to withstand frequent replanting can assist in the living wall's ease of setup and of use. Also, living walls that are planned to facilitate intensive interaction with their users should be designed to ergonomically fit those users' height ranges.

An additional performance parameter studied in the course of this work was embodied energy, an issue that should be considered and optimised for all living wall designs. Additional consideration should be given to plant selection in terms of growth speed and pattern, climate zone, amount of light, precipitation, salinity, and wind (Perini, Ottele, Haas, & Raiteri, 2012; Wood et al., 2014). Financial considerations were not addressed in this work.

8.2 Balancing Design Decisions for Combined Living Wall Benefits

The previous section clarifies how the same design parameter values may influence the various performance parameters differently. A prime example of the inherent difficulty of balancing competing requirements is deciding upon the optimum plant selection for a living wall that is expected to produce food as well as enhance natural habitat by simultaneously producing food for the living wall users, and providing shelter and food to local fauna. This section uses the knowledge discussed in the previous section to identify and discuss a few contradictions and trade-offs between such design parameter values and suggests possible resolutions.

8.2.1 Plant selection— size and density

According to the results of this work, the recommended properties for plants of a living wall for building cooling energy savings were an LAI above 3 and heights over 10 centimetres. High density and size of vegetation is also valuable in terms of appearance.

However, when considering plant characteristics for a food producing living wall, these plant heights and LAIs cannot be taken for granted. Vegetables are typically grown in cycles measured in days after emergence. During a typical 40 to 120 day cycle, plants start from ground level and gradually reach their mature height, as illustrated by the following examples:

- Depending on cultivar and climate, lettuce reaches a height of 15 centimetres between day 80 and day 140 (Waycott, 1995);
- Dill reaches a height of 12 to 20 centimetres at about day 28 (Frąszczak, Knaflewski, & Ziombra, 2008);
- Parsley reaches a height of 8 to 18 centimetres at about day 28 (Frąszczak et al., 2008); and
- Maize reaches a height of 110 to 160 centimetres at about day 60 (Chabot, Antoun, & Cescas, 1996).

Young plants' LAI is close to 0 at the beginning of the growing cycle. As they grow, the LAI increases (e.g., red beet reaches LAI = 3 around day 70; lettuce reaches LAI = 1 around day 45 and an LAI of 4 around day 60), in some cases (e.g., lettuce) reaching values higher than 5 (Tei, Aikman, & Scaife, 1996).To create an edible living wall with an average LAI of at least 3 and a height of at least 10 centimetres, a possible design principle would be to plan for a mix of young and adult vegetable plants and/or small varieties with larger ones, to ensure that enough large vegetable plants are evident at every point in order to supply ongoing thermal and aesthetic benefits.

8.2.2 Plant selection: type of plants

Available plant choices for a living wall can be divided into edible/non-edible, perennial/seasonal, and endogenous/global, to name just a few potential considerations. Some can be combined, while others are contradictory. For example, edible plants are usually seasonal and therefore less suited to offer both thermal benefits and appearance, as discussed in the previous section. Nevertheless, it may be possible to find some edible plants that are large and evergreen (e.g., berries and herbs). It may also be possible to select endogenous plants that are dense and high enough to contribute thermal benefits for living wall designs that promote urban nature and biodiversity. Selecting endogenous plants may also improve the living wall's water efficiency, as the plants are accustomed to the local climate precipitation patterns.

8.2.3 Growing substrate type and thickness

The results of this work demonstrate that a thick growing substrate not only contributes to living walls' thermal benefits by providing a better insulation layer, but it also allows a greater variety of plants to grow in it and to reach a larger size. For the systems used in the edible living wall study, the growing substrate thickness varied according to the system's morphology. The values of growing substrate thickness for each of the living walls systems are shown in Table 8.2.

Table 8.2: Maximal and average thickness of substrate for each living wall

system

	Maximal Thickness	Average Thickness
Reclaimed Pallet	16 cm	12 cm
Aria	17 cm	11 cm
ELT	9 cm	9 cm
Invivo Pocket	20 cm	8 cm
Domino Planter	7 cm	7 cm
Woolly Pocket	16 cm	6 cm

Using the average thickness as an indicator, the energy simulation results suggest that all living wall systems could have a significant cooling effect. If thermal performance were the priority, systems with higher thicknesses should be used, but that decision must be balanced against the disadvantages of using a thicker substrate: ease of setup (user experience), levels of embodied energy, and overall weight loads. A choice must also be made between organic and inorganic growing substrate. Organic substrate will gradually decompose and require replenishment, while inorganic substrate involves intensive feeding of the vegetation. These should all be considered when choosing the living wall growing substrate type and dimensions.

8.1.1 Accessibility and dimensions

Edible living walls require a significant amount of maintenance work to prune, harvest and replant the plants, while living walls for thermal benefits generally require less maintenance (depending on the plants chosen). Therefore edible living walls positioned at an easily accessible area can be easier to maintain. Greater accessibility is also preferred for supplying educational and psychological benefits, since the key to these performance parameters is the interaction between the vegetation and the individuals who benefit from the living wall.

Another design solution for combining the benefits of edible living walls with those of thermal living walls is to use the accessible areas of the living wall for edible plants and the rest of the wall (i.e., higher than 2 m) for larger, low-maintenance plants with high density. Accessible areas include the portion that is accessible from the ground, areas adjacent to balconies or patios, or even small regions below and around windows. This kind of design is best suited to multi-story buildings with facades that are high and largely inaccessible.

8.1.2 Planting angle and substrate layer geometry

The results of this work recommend a planting angle for edible living walls that is as horizontal as possible. Using a horizontal planting angle was generally found to be better suited for frequent planting and therefore improves the likelihood of effective maintenance as well as successful personal interactions (i.e., educational and psychological benefits). However, horizontal planting angles affect the growing substrate geometry, making the substrate layer non-homogenous in its thickness (see Figure 4.9). How this influences the thermal benefits is not yet known, since the thermal study simulation of this work could only simulate a simple, smooth growing substrate layer.

8.1.3 Living wall orientation—amount of sunlight

A living wall's orientation determines the amount of sunlight received and was found to have an important influence on building energy savings. However, receiving a large amount of sunlight is also important for a food producing living wall. Other performance parameters are not directly influenced by the orientation of the living wall, unless specific types of plants require particular configurations of sun and shade. It is thus possible to maximise most benefits using any orientation, except for the thermal benefits and food production that require a large amount of sunlight to supply significant benefits.

8.1.4 Designing living walls with combined design functions

Although some living wall functions might not coincide with each other well, a mix of functions can be achieved using the following strategies:

- Educational/therapeutic and agricultural living walls require high accessibility and therefore can be combined with other functions by allocating the lower part of the wall to education/food production and the less accessible part to other functions.
- The choice of plants can usually take several factors into account. For example, when designing an aesthetic/promotional living wall, choosing plants with a large LAI will promote the wall’s thermal benefits, and the same can be said for plants that improve air quality. Choosing local plants can fulfil both an urban nature and a water sensitivity function.
- As thermal benefits and food production are optimised by incorporating equatorial orientations, it is possible to plan these facades as a thermal/edible living wall and use other facades for other functions.

Other methods for combining more than one function in a living wall design can be generated during a creative design process.

8.3 Summary of Synthesis

This chapter synthesises the findings from all three studies of the influence that design decisions have on living wall performance parameters and then compares those findings with the limited information found in the literature. The results support most of the literature’s findings, and contribute more specific and design-oriented details and considerations to the body of knowledge regarding living walls. The entire set of living wall design parameters and performance parameters that were presented in this chapter, is further developed into a parametric model of living walls (Section 9.1.4) as discussed in the next chapter.

9 Discussion: The Evolution of Living Wall Design

This research began by examining the modern city and aspiring to achieve future urban sustainability that integrates healthy ecosystems with human life and spawns 'reconciliation ecology (Francis & Lorimer, 2011). While modern cities generally have relatively little horizontal planting spaces, it is possible to integrate vegetation on the many unused vertical surfaces (Stav & Lawson, 2012). This opportunity is the fertile ground from which the budding living wall practice grows.

Despite the fact that living walls in their traditional form of direct green facades have existed for thousands of years (Perini, Ottelé, et al., 2011) and that modern living wall technology was introduced decades ago (Bartczak et al., 2013), living wall practice is only slowly gaining momentum. It is far from being widespread and is currently adopted mainly as a token statement to environmental ideals or as an aesthetic element. The literature review presented in Chapter 2 revealed a distinct lack of knowledge regarding the design of living walls and, more specifically, the relationship between their design and their performance. The findings of the studies in this work, however, indicate that living wall design decisions are directly connected to their performance in multiple environmental and social aspects. According to the findings, if proper design decisions were embraced, living walls' performance could be enhanced and their value to cities and society augmented. An increased focus on design could drive the evolution of living walls as a practice, speeding up its adoption and enhancing its integration into the built environment and its benefits to cities.

The next sections outline how this work's principal findings promote our understanding and advancement of the evolution of living wall practice. The discussion is structured according to the research's objectives:

1. suggesting and assessing both design options and the potential performance aspects of living walls;

2. assessing living wall 'dynamics'—finding patterns in the relationship between living wall design and their environmental and social performance; and
3. developing a theoretical basis for the design of living walls to promote urban sustainability.

9.1 New Design Options for Living Walls

This work explored the realm of living wall design decisions, revealing a rich and full spectrum of design parameters and values, only a fraction of which are considered by the current state of the art.

9.1.1 Shifting the focus away from technical challenges

As discussed in Chapter 2, existing research related to living wall design focuses on a typology of living walls guided by technology (see Figure 2.2). This focus indicates an emphasis on the designer's choice of living wall system. For example, selecting a 'green façade' system implies that no vertical growing substrate will be used and that a specialised irrigation is usually not required, whereas choosing a 'vegetated mat' system inherently implies that the mat will be the growing substrate and that a specific irrigation system will be required. Professional living wall training literature, such as "Green walls 101: Systems overview and design" (Green Roofs for Healthy Cities, 2008) focuses on living wall systems, on their maintenance and structural loads, as well as on selecting plants according to hardiness zones. Although living walls' potential benefits of living walls are presented, they are only minimally connected to design decisions—the emphasis is on how to handle technical challenges.

A few research papers offer general guidelines for designing a living wall. Perini, Ottele, Haas, and Raiteri (2012) developed a process tree to help make design decisions for living walls. It takes the climate, building characteristics, technologies, dimensions, and plant selection into account. However, Perini et al. do not consider the multiple performance parameters studied in the present work, but only include thermal benefits as well as economic benefits and costs. A technical paper by Loh (2008) discusses design decisions for living walls and covers orientation, plant selection, irrigation, maintenance, and costs, but here again, the connection between design decisions and living wall benefits is not made. Other living wall studies and writings describe the benefits and costs of living walls and document case studies of living wall projects, but when design decisions are addressed, they tend to focus on the technical considerations related to constructional load, maintenance, endurance of plants, and costs (Dunnett & Kingsbury, 2008; Hopkins & Goodwin, 2011; Sharp, Sable, Bertram, Mohan, & Peck, 2008). This emphasis on technical challenges and solutions is typical of technologies in their initial evolutionary stages, when professionals are required to prove the feasibility of the technology much more than they are expected to create innovative designs that may be more beneficial. That is to say, designers are more concerned with demonstrating that their living wall remains lush and intact and does not damage the building than they are with enhancing its environmental and social benefits. Within this kind of mindset, designers are required to choose from a limited set of options rather than having a much wider and more multidimensional range of possibilities.

9.1.2 Establishing living walls' potential for high performance

The main point of departure for this work was that living walls could actually enhance urban sustainability (see section 1.2) or, in other words, could perform well in various aspects. Indeed, the knowledge related to the performance of living walls was expanded owing to the studies done as data was collected pertaining to several performance aspects of urban living walls. This work's findings demonstrated that it was possible to design a domestic living wall that produced food. In fact, four of the six living wall systems that were examined in the edible living wall study were found to be suitable for food production (see Chapter 5). As outlined by the living wall users' survey findings presented in Chapter 6, living walls often performed well—the average 'overall successful' rating of living walls by their users was 4.14 (on a scale of 1–5). Finally, the findings also showed that it was possible to design a living wall that increased building energy savings significantly (see Chapter 7).

9.1.3 Multifaceted living walls for social performance

The survey results indicated that living wall users ranked the social performance parameters of their living walls higher than the environmental performance parameters—the average rating of environmental parameters was 3.0, while the average rating of social parameters was 3.6. According to Goleman (2009), this tendency may be related to the participants' inability to understand the true ecological impacts of their activities. "We no longer can rely on our astute attunement to our natural world…that lets native peoples find ways to live in harmony with their patch of the planet" (p. 45). Goleman claims that we need to relearn hidden environmental consequences using intellectual comprehension of scientific findings. It is therefore understandable that participants will be more sensitive to how people are influenced by their living walls than to how the walls influence the atmosphere, fauna, flora, and other environmental factors. This does not mean that living walls have less environmental than social impact, merely that they are perceived to have more impact in the social arena. Hence, conventional thinking actually promotes values that are more conducive to social benefits at the expense of environmental benefits. Living wall designers should take into account the importance of social benefits, and on the other hand, be assisted by emerging data and knowledge to attribute appropriate importance to environmental factors.

The interpretation of social performance in this work will now be explicated. According to previous research, aesthetic improvement is the leading factor in living wall installation decisions (Bartczak et al., 2013) as well as the leading performance criteria. The findings from the survey in the present work support that assertion, showing that aesthetics was the leading motivation for living wall users in Tel-Aviv (see Section 6.1.3). That said, the understanding of living walls' success should include an understanding of the full spectrum of interactions between the living wall and the people around them. People's experience of living walls includes their ability to see, smell, touch, prune, harvest, and learn from them. Given that range, the focus on the social benefits of living walls should not be limited solely to aesthetics. Living walls' contribution to human wellbeing, their educational values, and their ability to produce food comprise but some of the many potential aspects that should be evaluated when considering living wall performance.

To summarise the findings, then, this work demonstrated that the existing focus of living wall design decisions on technical issues creates a skewed reflection of the wide range of designs available for living walls. It also established the potential of living walls to perform well in several aspects and specifically stressed the richness of their potential social benefits. The richness inherent in the wide range of living wall design and living wall performance can be presented via a parametric model.

9.1.4 An emerging parametric model for living walls

In addition to expanding the knowledge of living wall design and performance, one of the corollaries of this work is to suggest a new way to think abstractly about living wall design. The application of parametric thinking to living wall design and to the organisation of the parameters in a hierarchy is detailed below.

Known parametric equation revisited

The concept of parametric study was introduced as part of this work's methodology in Section 3.3.2, and Rittel's (1971) abstract equation of living wall dynamics P=f(D,C) was presented and adopted as a starting point for the parametric model of living walls. In its explicit form, the living wall dynamics equation was a vector equation,

$$(p_1,p_2,\ldots,p_n)=f((d_1, d_2,\ldots, d_m),(c_1, c_2,\ldots c_l))$$

where $p_1 \ldots p_n$ are the performance parameters, $d_1 \ldots d_m$ are the design parameters, and $c1 \ldots c_l$ are the context parameters. The first aim of this work—expanding the knowledge about living walls' design decisions and performance—was achieved by studying the vectors *D*, *C*, and *P* (respectively representing design, context, and performance parameters). As design, context, and performance parameters were identified in the course of this research, a richer and more complex model of living wall parameters was constructed.

New parametric model combining design and context

One of the objectives of the first study was to identify living wall design parameters. The list of identified parameters is presented in Section 4.1.4. Additional design parameters were identified in the two studies that followed. During the analysis of the data, the organisation of design parameters as a list seemed deficient, and it was suggested that design parameters can be better described as a hierarchical structure wherein the overarching level includes the technology of living walls, their location, and plant selection (see Figure 9.1). The edible living wall study offers the example of the 'living wall system' parameter, a design parameter that implies the values of other design parameters such as 'substrate thickness' and 'planting angle'. The 'living wall system' design parameter is also a sub-parameter of the 'living wall technology' parameter. In this example alone, three levels of design parameters have been identified, with 'technology' at the top level, 'system' below it, and 'substrate thickness' further below. A more accurate description of *D* would thus be a tree of parameters with attached values, rather than a vector.

Another divergence of the model from the initial equation that was uncovered during this research was that the boundary between design and context is often muddied. For example, the type of building can be considered a design decision in some cases, but it can also be considered a context parameter, depending on whether the designer accepts the location as part of the design project definition. Since the boundary between design and context parameters changes from one design problem to the next, a more useful representation would be to group design and context together (see Figure 9.1). To accommodate this, a new model of living wall design parameters was based on the parameters identified in this work and then organised in a hierarchical manner to create a tree of design and context parameters. The entire inventory of parameters organised in a tree hierarchy is illustrated in the diagram below (see Figure 9.1).

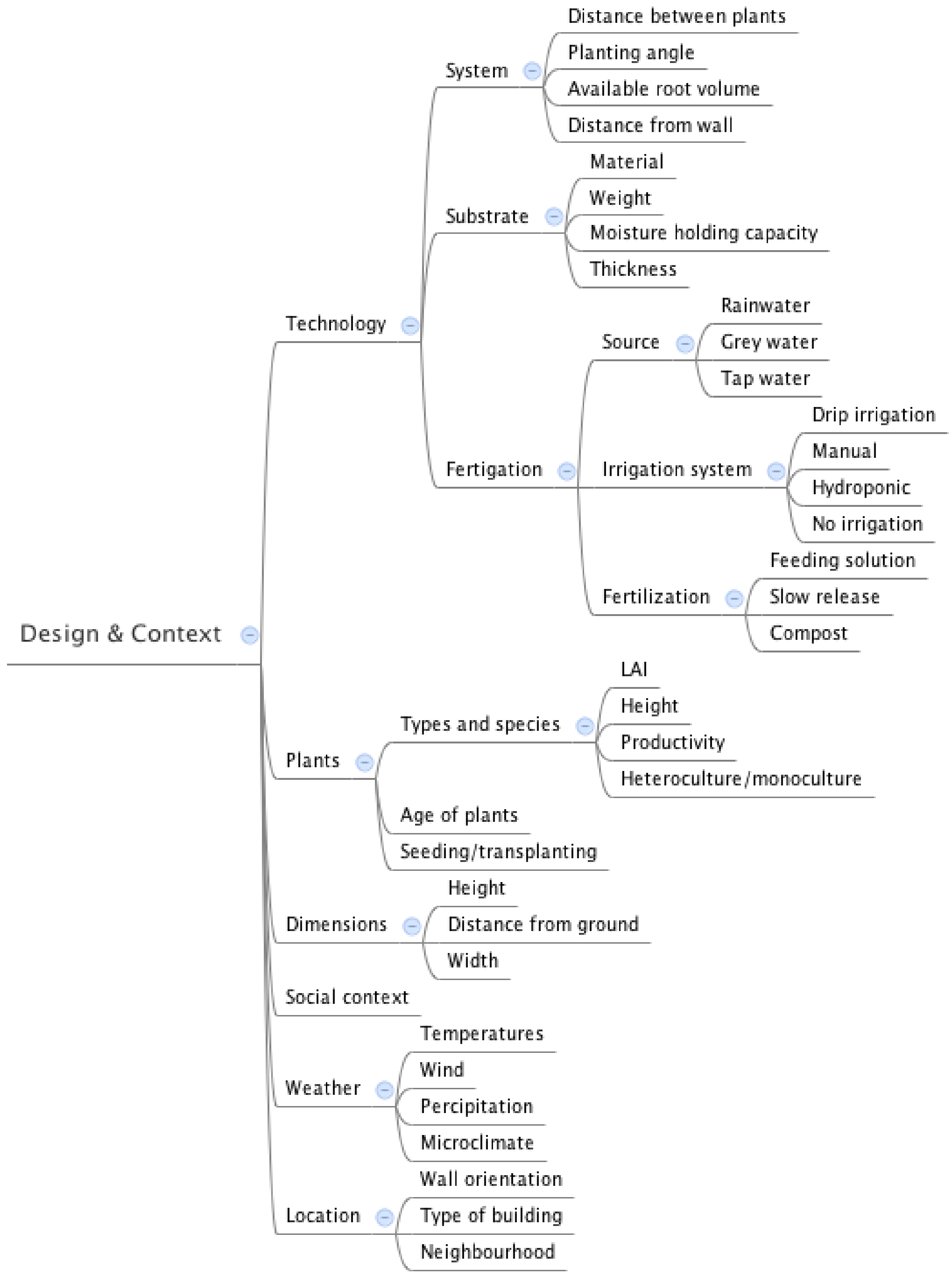

Figure 9.1: A new parametric model of living wall design and context

New hierarchical model of performance parameters

Similar to the above treatment of design parameters, performance parameters were identified through this research and their measurement processes were recognised. However, even if the assumption is made that each performance parameter has a well-established measurement method, the multidimensionality of their performance makes it difficult to rate different design solutions. The struggle to assess performance was also discussed in the context of sustainability assessment (see Section 3.2.2), and it has long been considered a recurring difficulty of design (see Rittel, 1971). It is therefore suggested that performance parameters also be organised hierarchically (see Figure 9.2). For example, an edible living wall can either be measured according to its food production or by the consequences of this food production (e.g., as energy savings due to reduced food miles, health benefits due to higher quality of food, etc.). The performance parameter hierarchy also gives rise to an additional concept of 'living wall function' that will be discussed in section 9.2.1. Therefore living wall performance parameters are best organised into a hierarchy that begins with the 'living wall function'. Each such function has related sub-parameters (e.g., food miles savings for an edible living wall). The inventory of performance parameters is shown in the diagram below (see Figure 9.2) organised in a tree hierarchy. As the knowledge about living walls develops, it is expected that this model will be expanded to contain more performance parameters, possibly with optional hierarchy levels.

9.2 Assessing Living Wall Dynamics

In this work, the concept of living wall dynamics that was derived from general systems theory terminology represents the relationships between living wall design decisions and living wall performance (see Section 3.2.1). Using parametric terminology, living wall dynamics are patterns generated in a living wall performance parameter value as a result of changes to a living wall design parameter value. As the detailed findings related to living wall dynamics presented in Chapter 8 indicate, many living wall design parameters were found to be significant in their influence on the living wall's performance.

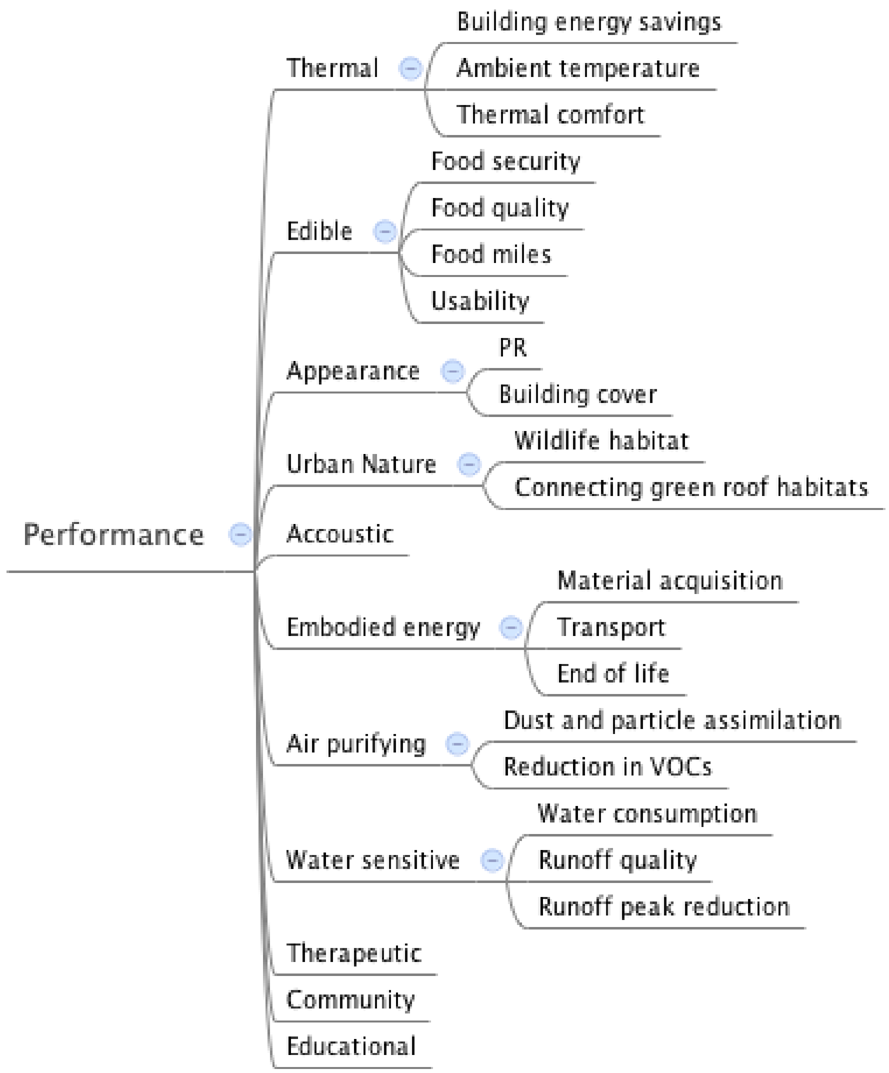

Figure 9.2: A new parametric model of living wall performance reflecting a hierarchy of parameters

Those findings showed that design decisions could affect whether a living wall made a positive or a non-positive contribution, as was the case. One such example is that living walls with an equatorial orientation were found to save cooling energy, while those with a polar orientation either saved very little energy or even occasionally incurred extra energy costs. Other design decisions (e.g., vegetation density, substrate thickness, and living wall dimensions, etc.) may not have such a dramatic effect but they nonetheless influence performance in important ways. The finding that edible living walls designed to hold less substrate volume per plant did not facilitate food production while those with greater substrate volume did, demonstrates another impactful design decision.

A living wall's social performance is primarily affected by its appearance. Improving the visual quality of urban landscape is considered one of the benefits of living walls, as individuals prefer natural landscapes over urban landscapes (Ulrich, 1986). Specifically, living walls "create living and evolving texture in the public realm, by developing colour and texture contrasts along building facades" (Hopkins & Goodwin, 2011, p. 47). In that sense, the appearance of living walls is a major factor in their perceived success (in addition to being a major motivation, as discussed in Section 9.1.3).

However, living wall design decisions were found to greatly influence other social performance aspects as well. They were found to have more therapeutic and educational potential and to better enhance a sense of community if they were large and located in public spaces. Although the studies carried out through the course of this work did not directly investigate design variations related to living walls' accessibility, it can be reasonably inferred that accessible living walls (defined as being at eye level and allowing direct contact) have increased educational and therapeutic performance outcomes.

9.2.1 Emergent functional typology for living walls

The suggested model of urban living walls' performance parameters demonstrates that these parameters can be usefully ordered to create parameters and sub-parameters (see Section 9.1.4). Therefore, when defining the desired performance for a living wall project, performance criteria are ideally set by first specifying the higher-level performance parameters (referred to as living wall functions). A previous study proposed that "living walls have multi-functional and deliberate environmental benefits to their built surroundings" (Loh & Stav, 2008, p. 5). This leads to the possibility of classifying living walls according to their deliberately designed performance, or living wall functions. This emergent functional typology is an innovative living wall typology guided by the proposed function of the living wall.

In this work, the theories of positive development (PD) and general systems theory (GST) were both used to shape the approach taken here to the general design problem of living walls. As was noted previously, both PD and GST agree that viewing a living wall holistically in the context of its environment is necessary to create successful design solutions (Birkeland, 2008; Skyttner, 2005). These theories also influenced the interpretation of the usage of the functional typology.

Understanding that changes in design parameter values may influence the performance of the living walls dramatically means that the most critical part of the living wall design process is defining the design objective. In fact, other researchers have recently suggested that a living wall's design objectives should be considered part of living wall design considerations (Wood et al., 2014). In this work, that suggestion is further developed by proposing that living wall benefits should not be considered a by-product of the living wall but, rather, its primary objective.

It is concluded that the design process for an urban living wall should start by identifying the design objective for that particular living wall. In the realm of performance-based design, the design objective is referred to as the *desired performance* (Papamichael & Protzen, 1993). It is recommended, then, that at the onset of the design process, the designer should first define the living wall's desired performance by setting or prioritising those high-level performance parameters that constitute the living wall's function/s. This approach looks at living walls as *transfunctional*—as objects of design that can and should fulfil a rich set of functions, creating a synergy between those various functions.

9.2.2 Transfunctional living walls

Designing living walls according to their desired functions invokes a new concept: *Transfunctional living walls*. Similar to the way a transdisciplinary approach articulates different levels of reality from various disciplines into coherence (Ramadier, 2004), a transfunctional design approach to living walls assumes that combining various functions enhances the overall performance of the living wall. In other words, the transfunctional living wall's benefits are greater than the sum of its performance-aspect-specific benefits.

A basic, function-based design approach advocates selecting a particular function and fulfilling it. The next step would be fulfilling two or more non-conflicting functions. A transfunctional living wall takes this process one step further by combining functions so that the living wall contributes in several performance aspects, overcoming contradictions via context-sensitive design solutions. The transfunctional perception of living walls, that living walls have the potential to fulfil multiple functions, is championed by this work's findings. Moreover, the three ideal types of living walls described in section 9.3.1 demonstrate how well integrating several functions in one project can enhance the resulting living wall. The following functional typology of living walls illustrates the principal building blocks of transfunctional living walls.

Thermal living walls improve buildings' insulation, and shade or cool the building envelope and its surroundings. The expected benefits from such living walls include saving building cooling and heating energy, improving occupants' thermal comfort, and mitigating UHI effects. Thermal living walls should have an equatorial (Pérez et al., 2011), west, or east orientation (Kontoleon & Eumorfopoulou, 2010), though the equatorial orientation offers the largest potential yearly energy savings (see Section 8.1.1). They should be designed with a thick, continuous substrate layer (Wong, Tan, Chen, et al., 2010) that has low solar absorbance and high capacity to hold water (see Section 8.1.1). The vegetation should be both dense (Wong et al., 2009) and tall (LAI>3, see Section 8.1.1), and the irrigation should keep the vegetation and substrate moist (see Section 8.1.1).

Edible living walls grow vegetables, herbs, and other beneficial plants such as medicinals. They usually require specialised irrigation and high maintenance and should therefore incorporate a readily accessible design. Edible living walls should receive a few hours of sun per day and provide six to eight litres of substrate for each plant's roots (see Section 8.1.2). A horizontal planting angle should be used if the plants are to be grown from seed. Planting a variety of vegetables and herbs (heteroculture) supplies the greatest harvest diversity (see Section 8.1.2) as well as improved pest resistance (Zhu et al., 2000), and if the spacing between plants is adaptable, then planting density should follow recommended values per plant (Bulson et al., 1997). Edible living walls should be easily accessible to facilitate daily maintenance and harvesting. Weather permitting, they should be watered daily, preferably by a drip irrigation system that is efficient and accurate (see Section 8.1.2).

Urban nature living walls are designed to recreate wildlife habitat within the city for birds, small mammals, insects, et cetera, or to form green corridors between parks and green roofs. Principally local plants should be used, and pests and weeds should be managed naturally (Grant, 2003). It may also be advisable to incorporate local, natural topsoil (Brenneisen, 2006). Urban nature living walls may provide food, water, refuge, and nesting options to birds, mammals, invertebrates and amphibians. This is done by choosing nectar, pollen or fruit rich plants. Alternatively, dense and prickly plant foliage may offer shelter (Grant, 2006, p. 46) and artificial roosting and nesting spaces for local fauna may be added, preferably in largely undisturbed areas that are located as high above ground level as possible (Chiquet et al., 2012).

Aesthetic/Promotional living walls are intended to be aesthetic building features or to hide unattractive areas of the building. The objective of a promotional living wall is to convey a message of environmental sensitivity. Both aesthetic and promotional living walls involve high visibility and may require intensive maintenance to retain their attractiveness. Aesthetic living walls should be large enough to enhance their impact (see section 8.1.9) and should be planted densely with tall, thick vegetation (Misgav, 2000). Plant health should be optimised by choosing low-maintenance plants and setting a routine of frequent maintenance visits. Promotional living wall patterns, logos, and even text can be created be devising a detailed living wall planting plan that takes seasonal vegetation changes such as flowering and wintering into account.

Educational living walls teach urbanites about ecology, gardening, botany, agronomy, et cetera, and they may include interactive features such as informational signs. Educational living walls should preferably be located on a large, outdoor wall of school buildings (see section 8.1.7) so they can be tended by students. Such living walls should be accessible to their target audience, either by installing them in naturally accessible locations and at appropriate heights or by designing facilities that help students interact with them by installing climbing steps for pre-school children or adjusting heights so they are accessible to patients in wheelchairs. If these living walls are planned to teach practical gardening, they should be designed for easy maintenance. The soil should be stable, and watering should be convenient.

Therapeutic living walls encourage people who view and interact with them to relax and enjoy the experience, or they assist in their healing process. In order to be more effective as a relaxing and mood-improving element, therapeutic living walls should be large (see Section 8.1.6). Like educational living walls, they should be accessible to their target audience, either by installing them in naturally accessible locations and at appropriate heights or by designing facilities that otherwise help users interact with them.

Community oriented living walls are intended to enhance community health, usually by encouraging social interaction and supplying a sense of community and cultural engagement. Community oriented living walls should be large and should be located in exposed, public areas (see Section 8.1.8) so they can contribute to community health (Tzoulas et al., 2007). Community oriented living walls may be integrated with community gardens to become centres of community life (Wood et al., 2014).

Air purifying living walls incorporate vegetation that can filter particles from the air as well as assimilate pollutants into their leaves. The efficiency of air purifying living walls is related to the amount of leaf surface area; they should therefore be as generously proportioned as possible and have the largest vegetation possible. Their vegetation should have leaves with either a 'hair' or wax cover so they can accumulate particulate matter on their leaf surface (Saebo et al., 2012). The air purification capabilities of exterior air purifying living walls are significantly enhanced if they are located close to pollutant sources such as busy roads and polluting factories. Exterior living walls can additionally improve indoor air quality when they are integrated with building ventilation systems (Rodgers, Hutzel, Dana, & Handy, 2012).

*Water sensitive living wall*s consume water efficiently, improve rainwater runoff quality, and modulate peak runoff. Water sensitive living walls may be integrated with a rainwater collection system in order to reduce or eliminate the use of potable water (Loh, 2008). Other alternatives are to use greywater or blackwater for irrigation. Greywater irrigation can create overflow water that is purified and so can be utilised for other purposes. Water sensitive living walls can be designed with a closed-loop irrigation system. They can also be designed to reduce evaporation if moisture-tight materials are chosen for the substrate containers. Thick growing substrate and specific plant selection may also reduce storm water runoff (Ostendorf et al., 2011) and thus help modulate runoff and improve runoff quality (Dunnett & Kingsbury, 2008).

*Acoustic living wall*s absorb and reduce street noise levels for both building occupants and pedestrians. Acoustic living walls should be designed to incorporate a thick substrate layer and a dense vegetation cover (Wong, Tan, Tan, Chiang, et al., 2010). They perform better when located a long distance from the noise source location (Ismail, 2013).

The functional typology outlined above is a valuable tool in the design process of transfunctional living walls, as the next section articulates.

9.3 Theoretical Basis for the Design of Transfunctional Living Walls

The third objective of this work was to synthesise the knowledge produced by the studies done with previous knowledge in order to generate a theoretical basis to help design living walls that promote urban sustainability. The parametric model of living walls—including the hierarchies of design, context, and performance parameters—is believed to be a useful tool for designers to understand the rich design space and potential performance aspects of living walls. The functional typology that maps design decisions for transfunctional living walls can be used to support the living wall design process by directing the designer to set the function/s of the living wall at the outset of the process. Once the living wall functions are set and prioritised, it is significantly easier to use the information garnered here about living wall dynamics to guide the designer's design decisions (i.e., design parameter values) that promote the wall's stated functions. The detailed knowledge describing living wall dynamics that was presented in Chapter 8 can be used to make specific design decisions oriented towards specific performance aspects. The recommended design of a transfunctional living wall should begin with understanding the design space and potential performance aspects, followed by prioritising the living wall's functions, and then focusing on making design decisions that support both environmentally and socially based functions to create a transfunctional living wall.

9.3.1 Three ideal transfunctional living walls

In order to demonstrate the design of living walls supported by the theoretical basis developed in this work, three different living wall scenarios that incorporate transfunctional typology and living wall dynamics are described. Each of these choices illustrates how a few functions that guide the design decisions related to them are fulfilled. These scenarios demonstrate how setting a desired function can lead to a beneficial design as well as to integrating several functions in a single living wall, such that they synergistically optimise the living walls' environmental and social benefits.

Case 1: Thermal and aesthetic transfunctional living wall

This living wall combines two major functions, thermal and aesthetic/promotional, that require a large vertical area and high visibility. It can also function as an urban nature living wall by adding a few additional design recommendations.

To achieve its thermal function, the living wall entirely covers a windowless, equatorial-facing facade of a large building in a warm climate (see Figure 9.3). The majority of its vegetation is made up of large plants that achieve high LAI levels. The growing substrate of the living wall is thick (10 cm) and has a high moisture retention capacity. The substrate uses an automatic irrigation system that keeps it moist during hot weather to facilitate evaporation. To promote its urban nature function, the living wall is planted with a mixture of many local plant species, some of which provide pollen, nectar, and seeds for wildlife.

Figure 9.3: Digital rendering of a living wall covering a building's equatorial-facing, windowless facade, showing a variety of local plants as well as nesting boxes for birds. The living wall supplies thermal, aesthetic, and urban-nature benefits simultaneously.

The growing substrate is based on local topsoil, and plants obtain additional nutrients through irrigated feed. Nesting boxes for birds are placed at the top part, and hive-holes for mason bees are incorporated throughout (see Figure 9.4). The living wall is planted densely to increase both its aesthetic function and its LAI. An attractive appearance is generated by using different species of plants and variable textures, flowers, and foliage colours to create patterns.

Because the thermal living wall has to hold a thick, continuous layer of substrate, it is based on a "cage"-style living wall system. The cages and the geotextile that holds the substrate are manufactured locally from recycled plastic. The cages are fixed to the wall with metal brackets that maintain an air gap between them and the wall to improve insulation and prevent excess moisture build-up on the building wall.

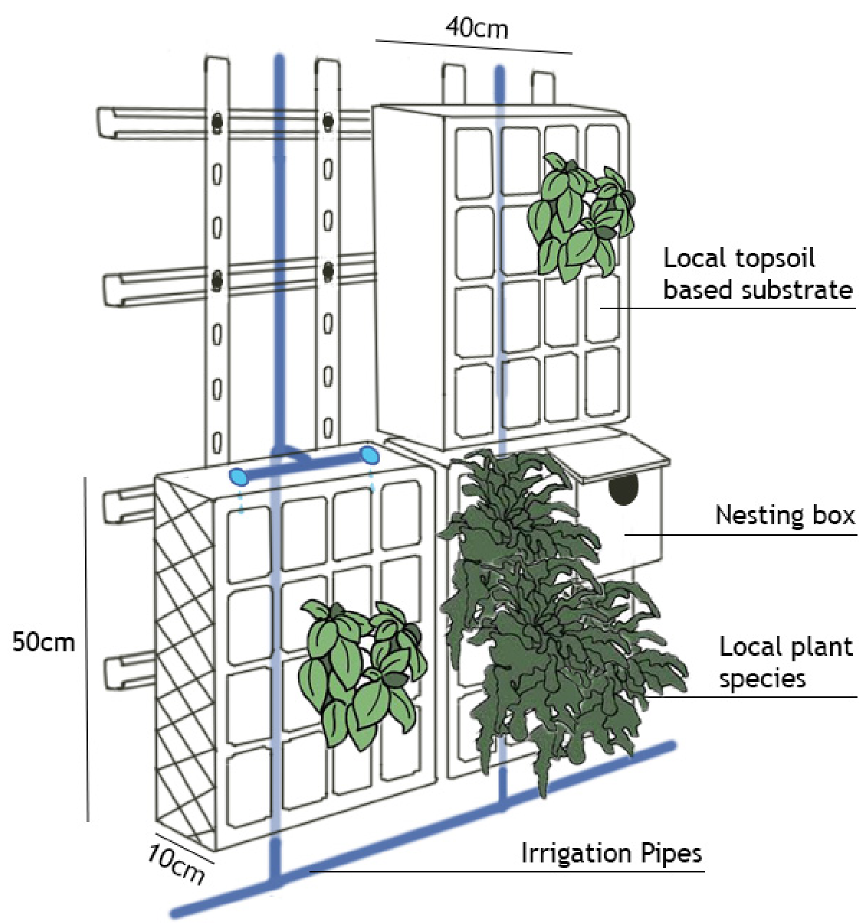

Figure 9.4: Details of thermal-urban nature living wall showing cage system, irrigation, and a nesting box.

Case 2: Socially oriented transfunctional school living wall

This living wall's primary function is education. It is also designed to be community oriented and water sensitive. Educational and community functions are combined since a living wall located on school grounds is in a public space and is readily accessible to students, their families, and the wider community.

In order to achieve its educational function, the living wall is located on an exterior wall of a school building that faces the school's yard (see Figure 9.5). It is a medium-sized living wall that spreads across the lower portion of the entire breadth of the wall. The lower part of the living wall is maintained by students and teachers as part of the school's curriculum, and it is based on modular living wall units that can be detached and taken to the classroom in order to change substrate and sow seeds, bulbs, and plants. The units are installed at eye level for easy access by students and teachers. The bottom part is planted according to the school's curriculum (e.g., geophytes, vegetables, or flowering plants) and can accommodate both gardening activities and botanical experiments.

Figure 9.5: Digital rendering of a school living wall showing the bottom part's accessibility to students and teachers and the low-maintenance upper portion based on climbers. The living wall is both water sensitive and educational, and it enhances a sense of community.

The living wall is accessible to the community after school hours, and the adjacent yard is used for casual community meetings and events. This promotes the living wall's community enhancement function. The upper, less accessible part of the wall is based on climbers supported by cables that add a permanent green cover and expand the wall's visibility. A rainwater tank that collects runoff from the school's roof supplies the drip irrigation system's water. Different parts of the living wall have separate drip lines to enable full control of the irrigation regime.

The upper part of this social living wall is based on a cable system made of coated steel or HDPE (Ottele et al., 2011) to minimise its environmental footprint. The lower part is based on locally manufactured panels that are made of recycled plastic and filled with local potting mix substrate. Much of the living wall's setup (specifically, filling the panels with substrate and planting them) can be done by the students.

Case 3: Domestic edible transfunctional living wall

In addition to being an edible living wall that covers an apartment balcony's wall and both sides of the banisters (see Figure 9.6), this small, domestic living wall's functions are aesthetic and therapeutic. It covers an area between 30 and 180 centimetres high from floor level, allowing convenient access for planting and harvesting. The residents of the apartment maintain the living wall's health and appearance. This pocket-style living wall system's horizontal planting angle allows the residents to start plants from seed. The substrate volume in the system is greater than seven litres per plant. This system allows DIY setup and may require drip irrigation, depending on the living wall users' preferences. Excess water drips from the living wall into troughs or planted boxes (see Figure 9.7) to avoid wetting the balcony floor.

The living wall incorporates a mixture of herbs (some of them perennial) planted on the balcony wall, as well as various seasonal vegetables and flowers that are planted on the banisters. The balcony grows a variety of species (heteroculture) to allow variety in vegetable types and sporadic harvest times as well as greater pest resistance. The herbs are clipped regularly, and vegetables are harvested as they mature and then replanted.

Figure 9.6: Digital rendering of balcony with vegetation on the wall and banisters. It shows a variety of herbs and vegetables growing in planted pockets. This living wall supplies food for the residents of the apartment as well as relaxation and beauty to an otherwise lifeless balcony.

The edible living wall is based on a pocket system that is manufactured locally from reclaimed/recycled materials. The system is fixed to the wall or banisters using standard screws and anchors. The growing substrate is a mixture of inert lightweight substrate (e.g., perlite) and compost produced from food scraps from the apartment's kitchen. New compost is added every season to the pockets to maintain fertility and compensate for organic matter loss.

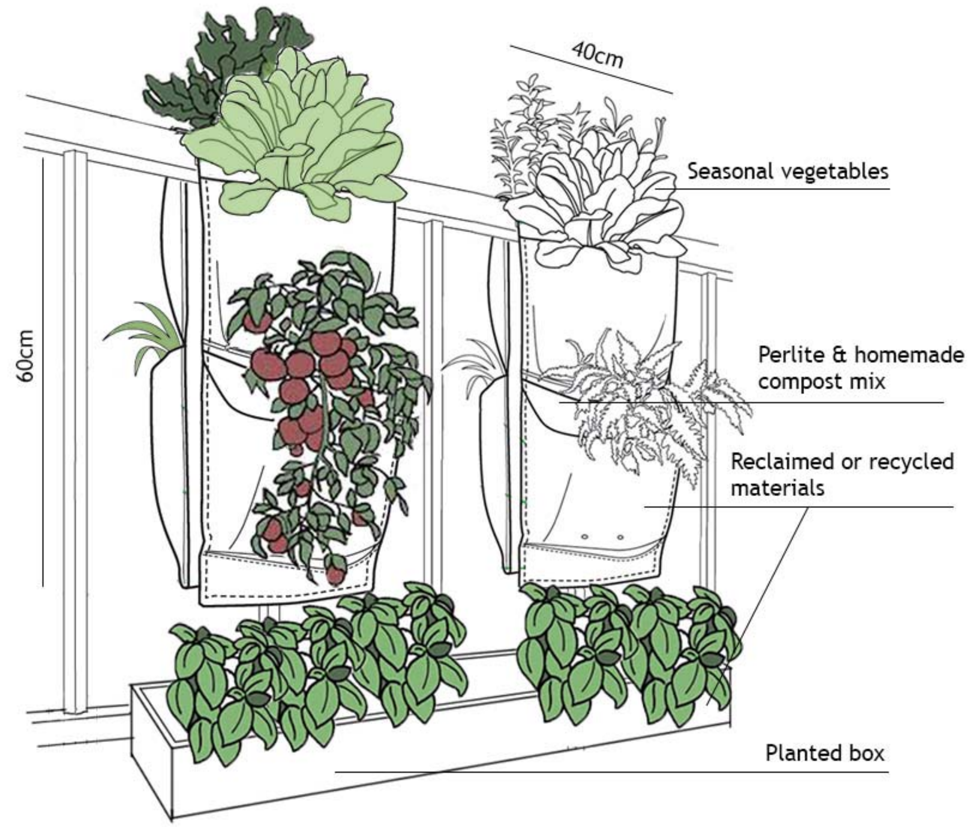

Figure 9.7: Details of domestic edible transfunctional living wall showing seasonal vegetables planted in pockets on balcony banisters with a planted box below.

9.4 Summary of New Design Knowledge

This work expands the body of knowledge related to living wall design and performance by mapping the living wall design parameters and performance parameters. It demonstrated that the design space for living walls is broader than the technology-oriented discourse that was the current state-of-the-art.

Although many living wall benefits are mentioned in previous research, the importance and variety of social benefits was undervalued. Moreover, most previous research does not connect living wall benefits to design decisions. This work focused on that connection (i.e., living wall dynamics) and resulted in more detailed and nuanced knowledge regarding the important influence design decisions have on the performance of living walls. This work also generated a new parametric model useful for the design and study of living walls. This model gave rise to a functional typology that is key to the process of living wall design. The functional typology, together with the living wall dynamics and the parametric model, constitute a new theoretical basis that supports the design of transfunctional living walls that optimise environmental and social benefits. The evolution of the practice of living walls is at a stage where such support is required in order to allow living walls to be widely adopted as an integral element promoting urban sustainability.

10 Conclusion: Transfunctional Living Walls Using a Parametric Approach

This chapter presents the outcomes of the present work in terms of their significance and contribution to knowledge. Section 10.1 presents the work's methodological contribution, while Section 10.2 describes its substantive contribution. The limitations of the present work are discussed and future avenues of related research are suggested in Section 10.3. It is claimed that the outcomes of this work may generate a change in the processes of living wall design, research, and decision-making.

10.1 Methodological Contribution of Parametric Study

The approach of most existing living wall studies is to prove that specific living walls in specific contexts can confer various benefits. Sometimes this approach quantifies these benefits and weighs them against the known costs. The departure point for the present research, however, was that living walls could help attain greater urban sustainability. Its research problem was to seek living wall designs that maximise their environmental and social benefits (see Section 1.3). This unique departure point and research problem led to the incorporation of parametric thinking into its methodology.

While studying the properties of a new technology might not always require a radically new research approach, this study's approach is derived from a design-oriented departure point and focuses on the relationship between design and performance. To assess this relationship, referred to herein as *living wall dynamics*, both the design and performance of living walls were studied parametrically. This research approach engages both architectural science and social science methods. The unique combination of a design approach with a parametric approach that originates in the exact sciences is normally only used in the realm of computer-aided design. In this work, the parametric approach highlighted patterns in living wall dynamics, and these patterns were then generalised to create knowledge useful for making design decisions to create transfunctional living walls.

10.1.1 Parametric modelling for performance-based design

Studying living walls parametrically as the object of design required the identification of design parameters as well as performance parameters and then the construction of a parametric model that encompassed both. The parametric model (see Section 9.1.4) created an abstract representation of a living wall in the style of a tree of parameters with attached values (see Figures 9.1 and 9.2). This model is well suited to living wall design, and it can be further extended with additional parameters and supplementary hierarchy levels as research into living walls expands.

Moreover, this work demonstrated that parametric modelling could be effectively applied to performance-based design. It is also useful for researching other objects of design, particularly when the relationship between design and performance is the focus. In short, parametric modelling is beneficial for any performance-based-design activity (Oxman, 2008) that involves a multifaceted performance function.

10.1.2 Combining parametric thinking with design research

The parametric thinking implemented here resulted in a preliminary parametric model for living walls, but that was only part of the impact it had on this work's research process. All of the studies incorporated parametric thinking. In addition to the straightforward parametric study of the building energy simulations, parametric thinking was utilised for the non-digital studies as well. First, design parameters were identified throughout the edible living wall case study's pilot stage. Parametric analysis of the data collected in the edible living wall case study was then performed. Parametric thinking also guided the composition of a parametric questionnaire and the parametric analysis of the survey results. In summary, the different ways in which parametric thinking was incorporated into (non-digital) design research methods constitute new methodological knowledge in design research.

10.2 Substantive Contribution of Transfunctional Living Walls

Creating living walls that integrate vegetation into the built environment is a relatively new practice (Loh, 2008). Although it has gained momentum in the last decade (Mazzali et al., 2013), the present work shows that large gaps in the body of academic knowledge remain. The most significant knowledge gaps identified in the literature review were the use of living walls for urban agriculture, the contribution living walls make to human wellbeing, and design-related issues concerning living walls' thermal benefits. It is claimed that the present work narrows these knowledge gaps.

Knowledge about living walls' dynamics generated by the present work encompasses numerous aspects. The three studies performed touched on many living wall performance aspects and generated knowledge that is significantly broader in scope (see Section 9.1.2). The knowledge created is based on living wall dynamics, and it informs design decisions to a greater extent than any previous work. The broad range of inquiry conducted inherently supports a holistic design approach to living walls, as is to be expected from a design-for-sustainability process (Birkeland, 2008).

In other words, the outcomes of this work not only narrow the identified knowledge gaps, they also ratify the premise that living walls can enhance urban sustainability (see Section 1.2). Enhancing urban sustainability using living walls is increasingly valuable in denser cities, where vertical surfaces are relatively abundant and where vegetation is scarcer.

10.2.1 Shifting decision making for living walls

Both the research literature and the findings of this work support the assumption that aesthetics is the leading motivation behind living wall installation decisions (see Section 9.1.3). In that vein, this work may help inform decision-makers in the built environment about the multitude of benefits conferred by living walls. More specifically, it could inform decision makers about the less explored options that living walls hold for urban agriculture and for wildlife habitat, and it may also supply decision makers with additional incentives for incorporating living walls into their plans. It is expected that further research will build upon the present work's outcomes and develop that knowledge into practical policies. For example, a strategy for promoting urban agriculture could include components of both vertical city farms and balcony micro-farms. Such a policy might offer recommendations regarding, for example, orientation, irrigation, substrate composition, and dimensions of edible living walls. Such policies can encourage the adoption of living walls more often and more rapidly.

10.2.2 Designing transfunctional living walls

Chapter 9 discussed the results of the present work and the theoretical lens it adopted to generate the concept of *transfunctional living walls*. This updated approach focuses on the role of design in creating living walls that confer multifaceted and synergistic environmental and social advantages. The process of designing a transfunctional living wall should be guided by both the multitude of functions that living walls can fulfil and by the synergy of functions spanning different types of performance aspects. This recommendation alone can be beneficial as it shifts the focus away from technical challenges and presents the opportunity for living walls that are holistically oriented towards environmental and social benefits.

The theoretical basis developed in the present work emphasises the dynamics of living walls and is structured around the transfunctional living wall. That theoretical basis includes the following:

- a parametric model of living walls (see Section 9.1.4),
- patterns in living wall dynamics (see Chapter 8),
- a functional typology of living walls (see Section 9.2.1), and
- ideal living wall types demonstrating how these components can be implemented (see Section 9.3.1).

This theoretical basis may guide designers to a more functionally oriented process that will, hopefully, focus the design of living walls towards enhancing environmental and social benefits. In other words, the knowledge required to overcome the technical challenges of living walls (related to structural loads, irrigation, and plant selection) is mature and it is now time to pursue a higher goal in living wall design: designs that address the living wall's desired functions, thereby optimising their environmental and social benefits.

10.2.3 A place for small domestic living walls

Another implication of the results is related to the present work's focus on domestic living walls. The emphasis of most existing research is on large living walls, usually installed in public areas. Also, most living wall projects mentioned in professional literature are located in public settings. Conversely, the three studies in this work centred upon domestic, small-scale living walls. In addition, one of the findings of the living wall user survey was that a majority of the living wall projects covered in the survey were small and located in domestic settings (see Chapter 6). As a result, this work focuses largely on the small domestic living walls, which have not heretofore received much attention in the scientific literature.

The potential impact of a greater number of small domestic living walls is high owing to the large amount of vertical surfaces that are available in residential areas (see Section 4.2.2). The cumulative mass of many small living walls could well make a significant contribution to urban sustainability. The outcomes of the present research may encourage the design and setup of domestic and small-scale living wall projects, inspired by the multiple potential benefits as well as their comprehensible setup and maintenance.

10.2.4 Benefits to multiple stakeholders

The outcomes of the present work can therefore benefit living wall designers (be they landscape architects, product designers, or other living wall professionals) who can ground their work in the theoretical basis generated by this work and use it to create living walls that enhance urban sustainability. The outcomes may also contribute to developers and builders' incentives to apply living wall technology based on more than aesthetic considerations. Lastly, it is hoped that policy makers will acknowledge the multifaceted performance of living walls and develop policies that encourage their frequent implementation. Living walls, whether small or large, domestic or public, can make a significant contribution to the sustainable city.

10.3 Limitations and Future Research

The present work, as any research-for-design work, developed a theoretical basis to support the design process. Blessing and Chakrabarti (2009) suggested that an additional *evaluation* stage should be performed after completing such research. The evaluation stage related to this work can determine whether the application of the proposed support does indeed lead to improved performance. This further research can assess the environmental and social performance of living walls that were designed using the theoretical basis developed in this work. This kind of evaluation is expected to generate more knowledge that will expand upon the theoretical basis developed here.

Likewise, the present work addresses the following specific knowledge gaps: how effectively living walls can be used for urban agriculture, the contribution they make to human wellbeing, and design-related issues affecting their thermal contributions. The methodology developed in this work can, in future, specifically address additional knowledge gaps related to living wall design—for example, understanding its influence on hydrology, acoustics, facade longevity, and economics. The relationship between design decisions and these performance aspects can be studied using parametric analysis and a parametric model similar to those used in this work.

Lastly, although the present work was based in Tel-Aviv, Chapter 7 outlined how it could be effectively applied to the climatic context of Brisbane. The present work's methodology is generalisable and can be used to study other climates and other urban morphologies. Although the majority of its theoretical basis (i.e., the parametric model) is relevant to any city, future research can fine-tune the knowledge about living wall dynamics presented here to specific cities and on larger scales.

10.3.1 Food production research drawbacks

The researcher conducted the entire food production research over a period of less than 18 months. This was not enough time to re-test some of the crops under improved conditions. In terms of physical resources, it was apparent that in some cases, the lack of a control group and of sufficient repetitions might have altered the accuracy of the results. For example, the fact that a specific crop was smaller in a particular system might have resulted from positional effects or from the individual weakness of that plant. It could however, also be true that root space was lacking and needed to be augmented. In other words, some parameters may require further study to unequivocally validate their influence on the performance parameters measured. Inductions derived from case study research are not generally as rigorous as those resulting from more data points. One of the inherent drawbacks of case study research is that the resulting inductions tend not to be as rigorous. On the other hand, case studies allow a wider range of issues and parameters in a complex system to be covered.

When measuring the harvest amount of the various living wall systems, the weight of the crops was the main metric, but that choice incurs the following drawbacks:

- Harvest diversity is not reflected in this metric, even though it confers benefits,
- The weight metric does not accurately reflect the advantages and disadvantages of each system when different types of crops are grown, and
- A weight metric awards higher scores to root and fruit vegetables, as opposed to relatively lightweight herbs and greens.

However, the weight metric was chosen since other options (i.e., counting units or comparing images) are even less accurate and do not allow numerical analysis. The weight metric is also the metric that is most commonly used in agronomic studies. Other aspects of each living wall system’s suitability to grow different types of crops and the diversity of crops are described and discussed separately from the issue of yield.

Future research of the relationship between design decisions and living wall productivity might include full-scale agronomic experiments based on the parameters and dynamics developed in the present work. Such experiments may well produce statistically rigorous guidelines for designing living walls for maximal productivity.

10.3.2 Survey limitations

Most of the participants in the questionnaire (77.3%) reported on living walls located at 'home'. The survey's focus on domestic living walls generated useful knowledge regarding that type, but living walls located in schools, offices, or public areas were represented by only 15 of the 66 participants. The small sample of non-domestic living walls diminished the *t* test-based statistical significance of many of the results analysis and thus limited the amount of knowledge that could be extracted from the survey relating to these types of living wall installations. Moreover, several living wall location options (including 'shop', 'university', 'cafe/restaurant', or 'nursing home') were not represented at all in the survey. It is possible that the performance perceptions of users of these other types of living walls will differ from those recorded here.

Most of the questionnaire respondents were living wall users who had made the decision to buy or build a living wall. However, the living wall designer, planner, or even the living wall owner would generally not be the user of large living walls on public buildings or in a commercial venue, for example. Further, were we to conduct a survey of the students in a school where a living wall was installed that excluded the teacher who was responsible for the project, we might expect different answers. The results might also differ if a survey of customers of a restaurant that featured a living wall or of random passers-by next to a public building living wall were conducted. In addition, since the survey's respondents were all customers of one firm, that firm's marketing materials might create a bias in their responses. Further work is required in order to understand the social impact of living walls within the broader circle of living wall owners as well as living wall users—the people who are exposed to living walls in a wider range of contexts.

10.3.3 Thermal simulation limits

The energy simulations that were part of the present work are based on a simple building model that is not sophisticated enough to replicate typical residential or commercial buildings in Tel-Aviv or Brisbane. Also, the simulation does not take into account internal gains generated by the people and equipment inside the building. A larger building type with more thermal mass might reduce the living wall's impact. That said, these simulation limits are expected to influence the absolute energy savings results and not the dynamics of the design parameters themselves.

The simulation model itself has a few technical limitations. It is based on a green roof module that was not designed to be applied to a vertical surface. One of the challenges is that the vegetation module only approximates wind and moisture calculations, a factor that can reduce accuracy. Additionally, the green roof and living walls within EnergyPlus's model must share the same parameter values in a single simulation. More flexibility in the definitions of the living walls would allow different parameter values for different living wall areas to be tested.

The simulation study also assumes that there would be plants found with specific characteristics (such as LAI and height values) suitable for use on vertical surfaces. It is assumed that these plants would thrive within the given light, wind, and irrigation conditions. This assumption is challenging when taking into account seasonal changes and different climates, since many plants change their characteristics over their lifecycle and across seasons. It would also be preferable to use real plant species or some combinations of species, with their corresponding parameters (mainly LAI), to allow realistic vegetation choices to be simulated. Growing substrate materials should also be modelled using real materials suitable for living walls (such as rockwool, synthetic felt, and hydrocell, to name a few). The actual physical properties of these materials, such as their thermal conductivity and water retention, should be used within the simulation.

10.4 Summary of Conclusion

The knowledge generated by the present work narrows the knowledge gaps identified, and ratifies the premise that living walls can enhance urban sustainability. The theoretical basis developed supports enhanced research of living walls and has the power to transform the design process of living walls. The concept of transfunctional living walls is useful for living wall design professionals as well as developers, builders, and policy makers. The methodological contribution made by this work can inspire future research that will use a parametric approach to understand and address additional design problems in varied contexts.

The anticipated design processes of living walls, supported by the theoretical basis developed by the present work, will result in a variety of transfunctional living walls that integrate well with their physical and societal context and that synergistically serve multiple environmentally and socially beneficial functions. Transfunctional living walls offer a viable method to integrate healthy ecosystems with human life as we seek more ways to realise sustainable cities.

Appendix A: Living Wall User Questionnaire

PARTICIPANT INFORMATION FOR QUT RESEARCH PROJECT
Living Walls and Their Potential Contribution to Urban Sustainability

QUT Ethics Approval Number 1300000191
RESEARCH TEAM
Principal Researcher: Yael Stav, PhD Student
Associate Researcher: Dr. Gillian Lawson, School of Design, Creative Industries Faculty, QUT
DESCRIPTIONThis project is being undertaken as part of a PhD study by Yael Stav. The purpose of this study is to understand living wall users, in order to better design living wall systems optimized for social and environmental benefits. You are invited to participate in this project because we think that you are using a living wall or interested in having a living wall.

PARTICIPATION
Participation will involve completing an anonymous questionnaire which will take approximately 7 minutes of your time. The questions are concerned with your living wall, or the living wall you would like to have. For example: "What systems are you using for your living wall?" and "Where is your living wall located?"

Your participation in this project is entirely voluntary. Your decision to participate or not participate will in no way impact upon your current or future relationship with QUT or with the researcher. If you do agree to participate you can withdraw from the project without comment or penalty. However as the questionnaire is anonymous once it has been submitted it will not be possible to withdraw.
EXPECTED BENEFITS
It is expected that this project will benefit you in the future, as the knowledge gained will be used for developing and designing living walls that are better suited to their users.
RISKSThere are no risks beyond normal day-to-day living associated with your participation in this project.

PRIVACY & CONFIDENTIALITYAll comments and responses are anonymous and will be treated confidentially unless required by law. The names of individual persons are not required in any of the responses.
Any data collected as part of this project will be stored securely as per QUT's Management of research data policy.
The data collected will be used in the principal researcher's thesis and possibly in other academic publications. If you are interested in getting the results please contact the primary researcher and the key findings will be sent to you when they are ready.

CONSENT TO PARTICIPATESubmitting the completed online questionnaire is accepted as an indication of your consent to participate in this project.

QUESTIONS / FURTHER INFORMATION ABOUT THE PROJECTIf have any questions or require further information please contact one of the research team members below.

Yael Stav
Dr Gillian Lawson
+972 0547 739 337 yael.stav@student.qut.edu.au
+61 7 3138 4359 g.lawson@qut.edu.au

CONCERNS / COMPLAINTS REGARDING THE CONDUCT OF THE PROJECTQUT is committed to research integrity and the ethical conduct of research projects. However, if you do have any concerns or

research integrity and the ethical conduct of research projects. However, if you do have any concerns or complaints about the ethical conduct of the project you may contact the QUT Research Ethics Unit on +61 7 3138 5123 or email ethicscontact@qut.edu.au. The QUT Research Ethics Unit is not connected with the research project and can facilitate a resolution to your concern in an impartial manner.
Thank you for helping with this research project. Please keep this sheet for your information.

Please select your language

- ○ English
- ○ תירבע

How did you find out about the concept of living walls/vertical vegetation?

- ○ Read about a living wall project
- ○ Saw a living wall product/system
- ○ Thought about it myself
- ○ Got a living wall as a present
- ○ Word of mouth

Other

....

If you found out about living walls from a product or project, what kind of living wall was that?

- ○ Climbers / vines
- ○ Based on pouches/pockets
- ○ Based on panels

Other

....

What system are you using for your living wall?

- ○ Invivo pouches
- ○ Climbers / vines
- ○ Pallet system

Other

....

What size is the wall/surface used for the living wall? (approximately)

- ○ 1-2 sqm
- ○ 3-5 sqm
- ○ 5-10 sqm
- ○ More than 10 sqm

How many living wall units are you using?

- ○ Single pocket/pallet
- ○ 2-8 pockets/pallets
- ○ 9 or more pockets/pallets

Where is the living wall located?

- ○ School / childcare
- ○ Nursing home
- ○ University
- ○ Home
- ○ Office
- ○ Shop
- ○ Cafe/restaurant
- ○ Public space

Other

....

What best describes the area in which your building is situated?

- ☐ Residential area
- ☐ Commercial area
- ☐ Mixed-use area
- ☐ Inner city
- ☐ Suburban

Other

....

What is the type of unit that the living wall belongs to?

- ○ Apartment
- ○ Private house
- ○ Public building
- ○ Commercial building/unit

Other

....

Please give us more information about the building

- ☐ Multistory
- ☐ Has balcony
- ☐ Has private backyard/garden
- ☐ Has common backyard/garden
- ☐ Singlestory
- ☐ Has rooftop

Other

....

What are the physical settings of your living wall?

- ○ Outdoor wall
- ○ Balcony wall
- ○ Balcony banisters
- ○ Fence
- ○ Stair railings
- ○ Rooftop
- ○ Indoors

Other

....

The living wall is facing:
(tick both North and East if the living wall is facing North-East for example)

- ☐ North
- ☐ South
- ☐ East
- ☐ West

How much sun does the living wall get?

- ○ More than 6 hours a day
- ○ 3-6 hours a day
- ○ Less than 3 hours a day
- ○ Indoors

What types of plants are grown in your living wall?

- ☐ Flowers
- ☐ Succulents
- ☐ Herbs and medicinals
- ☐ Vegetables
- ☐ Perennials

Other

....

If you are growing vegetables, what kinds of vegetables?

- ☐ Leaf vegetables (lettuce, chard, spring onion,chives, celery, arugula)
- ☐ Root vegetables (carrot, radish, beetroot, potatoetc)
- ☐ fruit vegetables (tomato, cucumber, eggplant, pepper,zucchini, chilli etc)
- ☐ Brassicas (cabbage, broccoli, kohlrabi, cauliflower, kaleetc)
- ☐ Beans (soy beans, black beans, red beans, snakebeans,snow peas etc)

Other

....

How do you water your living wall?

- ○ Hand watering
- ○ Manually operated drip irrigation
- ○ No water
- ○ Automatic drip irrigation
- ○ Grey water system

Other

....

Who is taking care of your living wall?

- ○ I am
- ○ My family
- ○ Gardener/s
- ○ Students

Other

....

Do you have any experience with gardening?

- ○ I'm a novice gardener
- ○ I'm an experienced gardener
- ○ I'm a landscape architect
- ○ I'm a professional horticulturist

Other

....

Is the living wall part of a personal or organisational sustainability plan?

- ○ It is not related to my idea of sustainability
- ○ It is not part of a plan but sustainability isimportant to me
- ○ It is part of my sustainability plan

Other

....

What are your reasons for using a living wall?

- ☐ It looks nice
- ☐ It improves air quality
- ☐ It's unique
- ☐ It helps educate others
- ☐ It saves floor/ground space
- ☐ For growing herbs and vegetables
- ☐ It adds nature into the city
- ☐ It reduces the heat in summer
- ☐ It's “green”

Other

....

How would you rate your living wall as:

	Not at all				Very much
Energy efficient	○	○	○	○	○
Water sensitive	○	○	○	○	○
Low embodied energy	○	○	○	○	○
Biodiversity enhancer	○	○	○	○	○
Urban agriculture facility	○	○	○	○	○
Enhancing sense of community	○	○	○	○	○
Educational	○	○	○	○	○
Relaxing & mood improving	○	○	○	○	○
Overall successful	○	○	○	○	○

Are there any suggestions or comments you would like to make?

- ○ No suggestions or comments
- ○ My suggestions or comments

Comments

....

Appendix B: Thermal Simulation Results Data

The following tables were used to record the output of the various simulation runs, to group them according to parameter manipulations, and to analyse the results. Tables of data that were presented in Chapter 5 are not repeated.

LAI

	LAI	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0**	614,978	69%	6,905,506	-74%
Building with Green Roof and Living Walls	**1**	600,906	69%	5,357,120	-35%
Building with Green Roof and Living Walls	**2**	629,899	68%	4,126,108	-4%
Building with Green Roof and Living Walls	**3**	671,765	66%	3,326,743	16%
Building with Green Roof and Living Walls	**4**	709,118	64%	2,878,388	28%
Building with Green Roof and Living Walls	**5**	704,067	64%	2,871,645	28%

Substrate Thickness

	Substrate Thickness	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**6**	5,296	44%	3,832,794	2%
Building with Green Roof and Living Walls	**8**	5,089	46%	3,204,757	18%
Building with Green Roof and Living Walls	**10**	4,782	50%	2,701,694	31%
Building with Green Roof and Living Walls	**15**	4,059	57%	1,939,441	50%

Vegetation Height

	Plant Height	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.1**	5,621	41%	3,236,338	16.9%
Building with Green Roof and Living Walls	**0.2**	5,426	43%	3,224,885	17.2%
Building with Green Roof and Living Walls	**0.3**	5,089	46%	3,204,757	17.7%
Building with Green Roof and Living Walls	**0.4**	4,763	50%	3,184,783	18.2%
Building with Green Roof and Living Walls	**0.5**	4,494	53%	3,163,634	18.8%

Leaf Reflectivity

	Leaf Reflectivity	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.1**	653,248	67%	3,538,145	11%
Building with Green Roof and Living Walls	**0.18**	661,382	66%	3,350,077	16%
Building with Green Roof and Living Walls	**0.22**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.25**	668,015	66%	3,198,038	19%
Building with Green Roof and Living Walls	**0.3**	672,766	66%	3,100,263	22%

Leaf Emissivity

	Leaf Emissivity	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.8**	626,127	68%	3,361,542	15%
Building with Green Roof and Living Walls	**0.9**	652,536	67%	3,293,517	17%
Building with Green Roof and Living Walls	**0.95**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.97**	670,202	66%	3,249,420	18%
Building with Green Roof and Living Walls	**1**	677,496	66%	3,230,969	19%

Minimum Stomatal Resistance

	Min Stomatal Res.	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**50**	702,680	64%	3,105,618	22%
Building with Green Roof and Living Walls	**120**	677,923	66%	3,199,271	19%
Building with Green Roof and Living Walls	**180**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**220**	658,952	67%	3,300,552	17%
Building with Green Roof and Living Walls	**300**	649,509	67%	3,370,439	15%

Roughness

	Roughness	Heating Total [kJ]	Heating Energy Savings	Cooling Total [kJ]	Cooling Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**VerySmooth**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**MediumSmooth**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**VeryRough**	665,520	66%	3,262,179	18%

Conductivity of Dry substrate

	Conductivity of Dry substrate	Heating Total [kJ]	Heating Energy Savings	Cooling Total [kJ]	Cooling Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.2**	525,587	73%	2,634,239	34%
Building with Green Roof and Living Walls	**0.3**	611,617	69%	3,022,829	24%
Building with Green Roof and Living Walls	**0.4**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.5**	700,696	64%	3,420,792	14%
Building with Green Roof and Living Walls	**0.7**	743,764	62%	3,618,888	9%
Building with Green Roof and Living Walls	**1**	776,609	61%	3,776,885	5%

Density of Dry substrate

	Density of Dry substrate	Heating Total [kJ]	Heating Energy Savings	Cooling Total [kJ]	Cooling Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**300**	930,330	53%	4,109,405	-3%
Building with Green Roof and Living Walls	**500**	771,362	61%	3,583,833	10%
Building with Green Roof and Living Walls	**641**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**800**	563,240	71%	2,960,673	25%
Building with Green Roof and Living Walls	**1000**	464,601	76%	2,665,672	33%
Building with Green Roof and Living Walls	**2000**	258,565	87%	2,017,997	49%

Specific Heat of Dry substrate

	Specific Heat Of Dry substrate	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**501**	936,499	52%	4,131,599	-4%
Building with Green Roof and Living Walls	**800**	798,255	59%	3,668,447	8%
Building with Green Roof and Living Walls	**1100**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**1300**	588,338	70%	3,034,827	24%
Building with Green Roof and Living Walls	**1600**	494,436	75%	2,755,896	31%
Building with Green Roof and Living Walls	**2000**	404,510	79%	2,480,558	38%

Thermal Absorptance (substrate Emissivity)

	Thermal Absorptance	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.81**	620,431	68%	3,377,158	15%
Building with Green Roof and Living Walls	**0.85**	633,967	68%	3,341,673	16%
Building with Green Roof and Living Walls	**0.95**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.97**	671,035	66%	3,246,224	18%
Building with Green Roof and Living Walls	**1**	679,525	65%	3,225,037	19%

Solar Absorptance of Substrate

	Solar Absorptance	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.4**	712,497	64%	2,599,746	35%
Building with Green Roof and Living Walls	**0.6**	688,304	65%	2,918,673	26%
Building with Green Roof and Living Walls	**0.8**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.85**	659,584	66%	3,350,284	16%
Building with Green Roof and Living Walls	**0.9**	654,031	67%	3,442,453	13%

Visible Absorptance of Substrate

	Visible Absorptance	Heating Total [kJ]	Heating Energy Savings	Cooling Total [kJ]	Cooling Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.51**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.7**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**1**	665,212	66%	3,261,191	18%

Saturation Volumetric Moisture Content of the Substrate Layer

	Saturation Volumetric Moisture content	Heating Total [kJ]	Heating Energy Savings	Cooling Total [kJ]	Cooling Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.11**	629,140	68%	3,871,629	2%
Building with Green Roof and Living Walls	**0.22**	656,093	67%	3,457,855	13%
Building with Green Roof and Living Walls	**0.32**	663,228	66%	3,312,329	17%
Building with Green Roof and Living Walls	**0.4**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.7**	667,899	66%	3,188,587	20%
Building with Green Roof and Living Walls	**1**	669,426	66%	3,165,111	20%

Residual Volumetric Moisture Content of the Substrate Layer

	Residual Volume Moisture conten	Heating Total [kJ]	Heating Energy Savings	Cooling Total [kJ]	Cooling Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.01**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.03**	656,551	67%	3,305,277	17%
Building with Green Roof and Living Walls	**0.06**	642,937	67%	3,397,359	14%
Building with Green Roof and Living Walls	**0.1**	620,340	68%	3,642,243	8%

Initial Volumetric Moisture Content of the Substrate Layer

	Initial Volumetric Moisture Content	Heating		Cooling	
		Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--
Building with Green Roof and Living Walls	**0.11**	664,929	66%	3,263,064	18%
Building with Green Roof and Living Walls	**0.2**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**1**	671,798	66%	3,238,810	18%

Irrigation Amounts

	7:00-9:00 (m/hr)		Heating		Cooling	
	Summer	Rest of year	Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building		1,967,300	--	3,970,486	--	
Building with Green Roof and Living Walls	**0.0000**	**0.0000**	674,838	66%	4,457,937	-12%
Building with Green Roof and Living Walls	**0.0010**	**0.0000**	676,348	66%	4,268,231	-7%
Building with Green Roof and Living Walls	**0.0010**	**0.0010**	673,708	66%	3,705,493	7%
Building with Green Roof and Living Walls	**0.0020**	**0.0020**	665,925	66%	3,252,118	18%
Building with Green Roof and Living Walls	**0.0024**	**0.0018**	665,212	66%	3,261,191	18%
Building with Green Roof and Living Walls	**0.0030**	**0.0030**	664,232	66%	3,188,641	20%

Thermal Comfort 24h

	Min-Max C°		Heating		Cooling	
			Total [kJ]	Energy Savings	Total [kJ]	Energy Savings
Bare Building	**19**	**25**	534,446		2,297,528	
Building with Green Roof and Living Walls	**19**	**25**	89,941	83%	1,809,861	21%
Bare Building	**20**	**24**	1,967,300		3,970,486	
Building with Green Roof and Living Walls	**20**	**24**	665,212	66%	3,261,191	18%
Bare Building	**21**	**23**	4,393,724		6,002,820	
Building with Green Roof and Living Walls	**21**	**23**	2,150,855	51%	5,229,053	13%

Appendix C: Living Wall Systems Harvest Log

The harvest log for the year 2012 is presented in Table 10-1. For each of the harvested vegetables, the weight and type was recorded, as well as its living wall system origin and month of the year. Weight is in grams rounded to 10 gr increments.

Table C: Edible living wall study – harvest log

Month	Crop	Weight [gr]	Plant Category	System
January	Lettuce	1600	Leaf Vegetables	Invivo Pocket
January	Radish	30	Root Vegetables	Invivo Pocket
January	Lettuce	600	Leaf Vegetables	ELT
January	Spring onion	80	Herbs	Woolly Pocket
January	Cherry tomato	200	Fruit Vegetables	Aria
January	Parsley	160	Herbs	Invivo Pocket
January	Rocket	60	Leaf Vegetables	Domino Planter
February	Parsley	160	Herbs	Invivo Pocket
February	Rocket	80	Leaf Vegetables	Domino Planter
February	Lettuce	800	Leaf Vegetables	Invivo Pocket
February	Lettuce	800	Leaf Vegetables	Woolly Pocket
February	Spring onion	80	Herbs	ELT
February	Purple basil	70	Herbs	Aria
February	Purple basil	70	Herbs	Woolly Pocket
March	Kale	500	Brassicas	Aria
March	Cabbage	2400	Brassicas	Aria
March	Cabbage	1800	Brassicas	Woolly Pocket
March	Cabbage	600	Brassicas	Invivo Pocket
March	Lettuce	800	Leaf Vegetables	Invivo Pocket
March	Rocket	60	Leaf Vegetables	ELT
March	Lettuce	800	Leaf Vegetables	Domino Planter
March	Chilli Pepper	200	Fruit Vegetables	Aria
March	Carrots	800	Root Vegetables	Invivo Pocket
April	Mint	80	Herbs	Aria
April	Lettuce	600	Leaf Vegetables	Woolly Pocket
April	Lettuce	800	Leaf Vegetables	Invivo Pocket
April	Parsley	100	Herbs	Domino Planter
May	Radish	10	Root Vegetables	Woolly Pocket
May	Fennel	500	Leaf Vegetables	Invivo Pocket

Month	Crop	Weight [gr]	Plant Category	System
May	Basil	70	Herbs	Pallet
May	Cherry tomato	500	Fruit Vegetables	Aria
May	Lettuce	800	Leaf Vegetables	Invivo Pocket
May	Mint	80	Herbs	Domino Planter
June	Tomato	1000	Fruit Vegetables	Aria
June	Cherry tomato	200	Fruit Vegetables	Woolly Pocket
June	Kale	500	Brassicas	Pallet
June	Zucchini	800	Fruit Vegetables	Pallet
June	Lettuce	3200	Leaf Vegetables	Invivo Pocket
June	Eggplant	200	Fruit Vegetables	Aria
June	Snake Bean	250	Legumes	Invivo Pocket
June	Mint	180	Herbs	Aria
June	Sage	30	Herbs	Woolly Pocket
June	Radish	20	Root Vegetables	Invivo Pocket
June	Basil	70	Herbs	Woolly Pocket
June	Parsley	100	Herbs	Pallet
June	Chard	200	Leaf Vegetables	Invivo Pocket
July	Tomato	1000	Fruit Vegetables	Pallet
July	Cherry tomato	1000	Fruit Vegetables	Aria
July	Snake Bean	260	Legumes	Invivo Pocket
July	Basil	70	Herbs	Woolly Pocket
July	Basil	70	Herbs	Pallet
July	Sage	30	Herbs	Invivo Pocket
July	Rosemary	40	Herbs	Woolly Pocket
July	Lettuce	800	Leaf Vegetables	Invivo Pocket
July	Eggplant	500	Fruit Vegetables	Woolly Pocket
July	Spring onion	80	Herbs	Invivo Pocket
July	Parsley	100	Herbs	Aria
July	Chard	200	Leaf Vegetables	Woolly Pocket
July	Mizuna	40	Herbs	Invivo Pocket
July	Radish	80	Root Vegetables	Invivo Pocket
July	Zucchini	500	Fruit Vegetables	Pallet
July	Pepper	260	Fruit Vegetables	Invivo Pocket
July	Cabbage	600	Brassicas	Aria
July	Melissa	60	Herbs	Invivo Pocket
July	Mint	60	Herbs	Aria
July	Lemon geranium	80	Herbs	Invivo Pocket
July	Purple basil	60	Herbs	Invivo Pocket

Month	Crop	Weight [gr]	Plant Category	System
July	Maize	250	Maize	Pallet
August	Tomato	500	Fruit Vegetables	Invivo Pocket
August	Cherry tomato	500	Fruit Vegetables	Pallet
August	Cherry tomato	500	Fruit Vegetables	Invivo Pocket
August	Eggplant	250	Fruit Vegetables	Invivo Pocket
August	Pinto Bean	300	Legumes	Pallet
August	Spring onion	80	Herbs	Woolly Pocket
August	Mint	100	Herbs	Aria
August	Pepper	250	Fruit Vegetables	Invivo Pocket
August	Cabbage	600	Brassicas	Aria
August	Soybean	40	Legumes	Invivo Pocket
August	Mizuna	40	Herbs	Invivo Pocket
August	Rosemary	40	Herbs	Woolly Pocket
August	Basil	70	Herbs	Aria
August	Purple basil	70	Herbs	Invivo Pocket
August	Lemon geranium	80	Herbs	Invivo Pocket
August	Stevia	40	Herbs	Woolly Pocket
September	Kale	1000	Brassicas	Pallet
September	Cherry tomato	300	Fruit Vegetables	Invivo Pocket
September	Pepper	250	Fruit Vegetables	Invivo Pocket
September	Hot pepper	200	Fruit Vegetables	Aria
September	Pinto Bean	500	Legumes	Pallet
September	Pinto Bean	500	Legumes	Invivo Pocket
September	Spring onion	160	Herbs	Woolly Pocket
September	Mint	90	Herbs	Aria
September	Oregano	40	Herbs	Aria
September	Basil	70	Herbs	Invivo Pocket
September	Watermelon	600	Fruit Vegetables	Pallet
September	Melon	600	Fruit Vegetables	Pallet
September	Lettuce	800	Leaf Vegetables	Aria
September	Parsley	80	Herbs	Aria
September	Purple basil	70	Herbs	Invivo Pocket
September	Rosemary	40	Herbs	Woolly Pocket
September	Sage	30	Herbs	Woolly Pocket
September	Lemon geranium	80	Herbs	Invivo Pocket
September	Lemon grass	80	Herbs	Invivo Pocket
September	Stevia	40	Herbs	Woolly Pocket
October	Eggplant	100	Fruit Vegetables	Woolly Pocket

Month	Crop	Weight [gr]	Plant Category	System
October	Cherry tomato	320	Fruit Vegetables	Aria
October	Spring onion	80	Herbs	Woolly Pocket
October	Chives	50	Herbs	Aria
October	Pinto Bean	1000	Legumes	Invivo Pocket
October	Pinto Bean	200	Legumes	Aria
October	Basil	70	Herbs	Invivo Pocket
October	Lettuce	600	Leaf Vegetables	Aria
October	Rosemary	40	Herbs	Woolly Pocket
October	Purple basil	70	Herbs	Pallet
October	Oregano	40	Herbs	Woolly Pocket
October	Squash	2000	Fruit Vegetables	Pallet
November	Pinto Bean	800	Legumes	Invivo Pocket
November	Pinto Bean	400	Legumes	Aria
November	Lettuce	800	Leaf Vegetables	Aria
November	Red lettuce	600	Leaf Vegetables	Aria
November	Chard	200	Leaf Vegetables	Invivo Pocket
November	Mizuna	40	Herbs	Woolly Pocket
November	Cherry tomato	400	Fruit Vegetables	Invivo Pocket
November	Chilli pepper	1000	Fruit Vegetables	Aria
November	Pepper	250	Fruit Vegetables	Invivo Pocket
November	Rosemary	40	Herbs	Woolly Pocket
November	Basil	70	Herbs	Invivo Pocket
November	Purple basil	70	Herbs	Invivo Pocket
November	Sage	30	Herbs	Woolly Pocket
November	Eggplant	800	Fruit Vegetables	Invivo Pocket
November	Spring onion	80	Herbs	Aria
November	Chives	50	Herbs	Aria
November	Lemon geranium	80	Herbs	Invivo Pocket
December	Spring onion	80	Herbs	Invivo Pocket
December	Chives	50	Herbs	Aria
December	Parsley	100	Herbs	Aria
December	Red lettuce	800	Leaf Vegetables	Invivo Pocket
December	Cherry tomato	380	Fruit Vegetables	Aria
December	Sage	30	Herbs	Woolly Pocket
December	Mint	90	Herbs	Aria
December	Basil	80	Herbs	Invivo Pocket
December	Chard	200	Leaf Vegetables	Invivo Pocket
December	Lemon grass	80	Herbs	Invivo Pocket

Month	Crop	Weight [gr]	Plant Category	System
December	Lettuce	800	Leaf Vegetables	Aria
December	Rosemary	40	Herbs	Woolly Pocket
December	Celery	800	Leaf Vegetables	Aria
December	Radish	20	Root Vegetables	Invivo Pocket
December	Mizuna	50	Leaf Vegetables	Invivo Pocket

Appendix D: Table of Survey responses

Respondent #	Submit date	Please select your language	How did you find out about the concept of living walls/vertical vegetation?	If you found out about living walls from a product or project, what kind of living wall was that?	What system are you using for your living wall?
1	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Pallet system
2	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Other
3	2013-05-19	English	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
4	2013-05-19	עברית	Saw a living wall product/system	Based on panels	Invivo pouches
5	2013-05-19	עברית	Saw a living wall product/system	Other	Other
6	2013-05-19	עברית	Other	Based on pouches/pockets	Invivo pouches
7	2013-05-19	English	Other	Based on pouches/pockets	Other
8	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
9	2013-05-19	עברית	Other	Based on pouches/pockets	Invivo pouches
10	2013-05-19	עברית	Read about a living wall project	Based on panels	Climbers / vines
11	2013-05-19	עברית	Other		Invivo pouches
12	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Pallet system
13	2013-05-19		Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
14	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Climbers / vines
15	2013-05-19	עברית	Other		Other
16	2013-05-19		Word of mouth	Based on pouches/pockets	Invivo pouches
17	2013-05-19		Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
18	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Other
19	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Climbers / vines
20	2013-05-19	English	Other	Climbers / vines	Invivo pouches
21	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
22	2013-05-19	עברית	Other	Based on pouches/pockets	Invivo pouches
23	2013-05-19	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
24	2013-05-20	עברית	Other	Climbers / vines	Climbers / vines
25	2013-05-20	עברית	Other	Based on pouches/pockets	Invivo pouches
26	2013-05-20		Other	Other	Other
27	2013-05-20	עברית	Got a living wall as a present	Other	Other
28	2013-05-20	עברית	Saw a living wall product/system	Based on pouches/pockets	Other
29	2013-05-20	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
30	2013-05-20	English	Saw a living wall product/system	Climbers / vines	Invivo pouches
31	2013-05-20	עברית	Other	Based on panels	Other
32	2013-05-20	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
33	2013-05-20	עברית	Read about a living wall project	Based on pouches/pockets	Pallet system
34	2013-05-20	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
35	2013-05-20	עברית	Other	Other	Other
36	2013-05-21	עברית		Climbers / vines	Climbers / vines
37	2013-05-21	עברית	Read about a living wall project	Based on pouches/pockets	Invivo pouches
38	2013-05-21	עברית	Saw a living wall product/system	Climbers / vines	Climbers / vines
39	2013-05-21	עברית	Other	Based on pouches/pockets	Invivo pouches

40	2013-05-21	עברית	Saw a living wall product/system	Other	Invivo pouches
41	2013-05-21	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
42	2013-05-21	עברית	Word of mouth	Based on panels	Pallet system
43	2013-05-21	עברית	Read about a living wall project	Based on pouches/pockets	Invivo pouches
44	2013-05-22		Other	Other	Invivo pouches
45	2013-05-23	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
46	2013-05-23	עברית	Saw a living wall product/system	Based on panels	Other
47	2013-05-23	עברית	Saw a living wall product/system	Based on pouches/pockets	Pallet system
48	2013-05-23	עברית	Other	Based on pouches/pockets	Other
49	2013-05-23	עברית	Read about a living wall project	Climbers / vines	Pallet system
50	2013-05-23	עברית	Word of mouth	Based on panels	Pallet system
51	2013-05-24		Read about a living wall project	Based on panels	Climbers / vines
52	2013-05-24	עברית	Saw a living wall product/system	Other	Other
53	2013-05-24	עברית	Other	Based on pouches/pockets	Invivo pouches
54	2013-05-24	English	Other	Based on pouches/pockets	Other
55	2013-05-24	עברית	Word of mouth	Based on pouches/pockets	Invivo pouches
56	2013-05-24	עברית	Saw a living wall product/system	Based on pouches/pockets	Climbers / vines
57	2013-05-24	English	Read about a living wall project	Based on pouches/pockets	Invivo pouches
58	2013-05-24	עברית	Read about a living wall project	Climbers / vines	Invivo pouches
59	2013-05-24	עברית	Saw a living wall product/system	Based on pouches/pockets	Climbers / vines
60	2013-05-25	עברית	Other	Based on pouches/pockets	Invivo pouches
61	2013-05-26	עברית	Saw a living wall product/system	Based on panels	Invivo pouches
62	2013-05-26	עברית	Read about a living wall project	Climbers / vines	Climbers / vines
63	2013-05-29	עברית	Thought about it myself	Based on pouches/pockets	Invivo pouches
64	2013-05-30	English	Read about a living wall project	Based on pouches/pockets	Pallet system
65	2013-05-30	עברית	Saw a living wall product/system	Based on pouches/pockets	Invivo pouches
66	2013-06-01	עברית	Word of mouth	Based on panels	Pallet system

What size is the wall/surface used for the living wall? (approximately)	How many living wall units are you using?	Where is the living wall located?	What best describes the area in which your building is situated?		What is the type of unit that the living wall belongs to?	Please give us more informa about the building				
		Home / Office / School / Public space	Mixed-use / Residential/ Commercial	Inner city / suburb		Multistory	Has balcony	Has private backyard/garden	Has common backyard/garden	Singlestory
1-2 sqm	2-8 pockets/pallets	H	R		Private house					+
More than 10 sqm	9 or more pockets/pallets	O		I	Commercial building/unit	+				
1-2 sqm	2-8 pockets/pallets	H	R		Private house			+		
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+				
3-5 sqm	9 or more pockets/pallets	H	R		Apartment	+				
3-5 sqm	2-8 pockets/pallets	H	R		Apartment	+				
1-2 sqm	Single pocket/pallet	H	R		Apartment	+			+	
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+	+			
1-2 sqm	Single pocket/pallet	H	R		Private house			+		
5-10 sqm	9 or more pockets/pallets	S		I	Public building	+			+	
1-2 sqm	2-8 pockets/pallets	H	R		Apartment		+		+	
3-5 sqm	2-8 pockets/pallets	H	R		Apartment		+			
1-2 sqm	2-8 pockets/pallets	H	R		Apartment			+		
5-10 sqm	2-8 pockets/pallets	H	R		Apartment		+			
5-10 sqm	9 or more pockets/pallets	H	R		Apartment		+			
3-5 sqm	9 or more pockets/pallets	H	R		Private house	+				
1-2 sqm	2-8 pockets/pallets	H	R		Private house			+		
3-5 sqm	2-8 pockets/pallets	H	R		Apartment			+		
3-5 sqm	Single pocket/pallet	H	R		Private house			+		
3-5 sqm	2-8 pockets/pallets	H	R		Apartment	+	+		+	
1-2 sqm	Single pocket/pallet	H	R		Apartment	+				
3-5 sqm	2-8 pockets/pallets	H	R		Apartment	+				
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+	+			
1-2 sqm	Single pocket/pallet	H	M		Apartment	+				
1-2 sqm	9 or more pockets/pallets	H		S	Private house			+		
5-10 sqm	Single pocket/pallet	H	R		Apartment					
3-5 sqm	9 or more pockets/pallets	H	R	I	Apartment	+	+			
1-2 sqm	Single pocket/pallet	H	R		Apartment		+			
1-2 sqm	Single pocket/pallet	H	R		Private house			+		
1-2 sqm	Single pocket/pallet	H	R		Apartment				+	
3-5 sqm	2-8 pockets/pallets	H	R		Private house					
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+	+			
1-2 sqm	2-8 pockets/pallets	S	M		Public building				+	
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+				
More than 10 sqm	9 or more pockets/pallets	S	M		Public building	+				+
3-5 sqm	Single pocket/pallet	H	R		Private house			+		
5-10 sqm	9 or more pockets/pallets	H	R		Private house			+		
More than 10 sqm	Single pocket/pallet	H	R		Private house			+		
3-5 sqm	2-8 pockets/pallets	H	R		Private house			+		

More than 10 sqm	9 or more pockets/pallets	O	M		Commercial building/unit		+			
More than 10 sqm	9 or more pockets/pallets	S	R		Public building					
1-2 sqm	Single pocket/pallet	S	R	S	Public building			+		
More than 10 sqm	9 or more pockets/pallets	H	R		Private house		+			
1-2 sqm	Single pocket/pallet	H	R		Apartment	+				
3-5 sqm	2-8 pockets/pallets	H		I	Apartment		+			
More than 10 sqm	9 or more pockets/pallets	H	M	I	Apartment	+				
3-5 sqm	2-8 pockets/pallets	H	R		Private house			+		
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+				
1-2 sqm	Single pocket/pallet	H	R		Apartment	+				
1-2 sqm	2-8 pockets/pallets	H		I	Apartment	+	+		+	
1-2 sqm	2-8 pockets/pallets	O	C		Public building					+
1-2 sqm	2-8 pockets/pallets	H	R		Private house			+		
3-5 sqm	9 or more pockets/pallets	S	R	S	Public building				+	
3-5 sqm	9 or more pockets/pallets	H	R		Apartment	+	+			
1-2 sqm	2-8 pockets/pallets	H	R		Apartment			+		
3-5 sqm	2-8 pockets/pallets	H	R		Apartment			+		
3-5 sqm	9 or more pockets/pallets	S	R		Public building	+				
3-5 sqm	9 or more pockets/pallets	S		I	Public building					+
1-2 sqm	Single pocket/pallet	H	R		Apartment			+		+
1-2 sqm	2-8 pockets/pallets	H	R		Apartment	+				
3-5 sqm	Single pocket/pallet	O	C		Commercial building/unit	+				
5-10 sqm	2-8 pockets/pallets	H	R		Private house			+		
1-2 sqm	2-8 pockets/pallets	Oth	R	S	Private house				+	+
5-10 sqm	9 or more pockets/pallets	P	M		Commercial building/unit					+
3-5 sqm	2-8 pockets/pallets	H	R		Apartment		+			
More than 10 sqm	9 or more pockets/pallets	S		S	Public building				+	+

ation	What are the physical settings of your living wall?	The living wall is facing:				How much sun does the living wall get?	What types of plants are grown in your living wall?					If you are growing vegetables, what kin vegetables?			
Has rooftop		North	South	East	West		Flowers	Succulents	Herbs and medicinals	Vegetables	Perennials	Leaf vegetables	Root vegetables	fruit vegetables	Brassicas
	Outdoor wall	North				Less than 3 hours a day					+				
	Outdoor wall		South	East		3-6 hours a day	+	+	+	+	+			+	
	Fence				West	3-6 hours a day			+			+			
	Indoors	North				Less than 3 hours a day			+			+			
	Indoors		South	East		More than 6 hours a day			+	+	+	+	+	+	+
	Balcony wall		South			3-6 hours a day			+						
	Fence	North	South	East	West	More than 6 hours a day	+	+	+	+		+		+	
	Balcony banisters	North			West	3-6 hours a day	+		+			+			
	Outdoor wall				West	3-6 hours a day				+		+			
	Outdoor wall		South	East		More than 6 hours a day		+	+						
+	Balcony wall		South			More than 6 hours a day			+	+		+			
	Balcony wall			East		3-6 hours a day			+			+			
	Outdoor wall			East		3-6 hours a day			+			+			
	Balcony wall	North				Less than 3 hours a day	+				+				
	Balcony banisters		South	East		More than 6 hours a day	+	+	+	+	+	+		+	
	Outdoor wall	North				Less than 3 hours a day			+	+		+			
	Fence		South			More than 6 hours a day			+			+		+	
	Fence				West	3-6 hours a day			+	+			+	+	
	Fence		South			3-6 hours a day					+				
	Balcony wall		South	East		More than 6 hours a day	+								
	Indoors	North		East		Less than 3 hours a day			+						
	Balcony wall	North		East		3-6 hours a day			+						
	Balcony wall		South		West	3-6 hours a day			+	+		+		+	
+	Rooftop	North				More than 6 hours a day	+		+					+	
	Fence		South			More than 6 hours a day	+		+	+		+	+	+	
	Outdoor wall			East		Less than 3 hours a day	+	+			+				
	Balcony wall				West	Less than 3 hours a day	+		+		+				
	Balcony wall	North		East		3-6 hours a day			+	+		+	+	+	
	Fence			East		Less than 3 hours a day			+			+			
	Indoors		South			3-6 hours a day			+						
	Fence	North				3-6 hours a day	+					+			
	Balcony wall		South			More than 6 hours a day	+	+	+					+	
	Outdoor wall		South			More than 6 hours a day	+		+	+		+			+
	Balcony wall		South	East		3-6 hours a day					+				
	Other		South			More than 6 hours a day	+	+	+	+	+	+		+	+
	Other			East		3-6 hours a day		+			+				
	Fence			East		3-6 hours a day			+						
+	Outdoor wall		South			More than 6 hours a day					+				
	Fence			East		3-6 hours a day	+			+				+	

	Balcony banisters			East		3-6 hours a day	+		+	+	+	+		+	
+	Balcony wall		South			More than 6 hours a day			+	+		+		+	
	Fence	North	South			3-6 hours a day	+		+	+		+			+
	Balcony wall				West	More than 6 hours a day			+			+			
	Fence	North				Less than 3 hours a day					+				
	Balcony wall	North				Less than 3 hours a day	+		+			+			
	Outdoor wall	North				More than 6 hours a day	+	+	+	+	+	+			+
	Fence	North				More than 6 hours a day	+	+	+	+		+		+	
	Outdoor wall	North			West	3-6 hours a day			+						
	Balcony wall		South		West	Less than 3 hours a day	+		+	+		+			
+	Balcony banisters	North		East	West	More than 6 hours a day			+	+		+		+	
	Outdoor wall		South			More than 6 hours a day	+		+	+		+		+	
	Fence	North				Less than 3 hours a day					+				
	Outdoor wall				West	3-6 hours a day		+	+		+				
	Balcony banisters		South		West	More than 6 hours a day		+							
	Balcony wall		South		West	3-6 hours a day			+	+		+		+	
	Outdoor wall		South			More than 6 hours a day			+	+		+			
	Outdoor wall	North				3-6 hours a day					+				
	Outdoor wall				West	3-6 hours a day	+	+	+		+				
	Outdoor wall		South			Less than 3 hours a day	+	+				+			
	Indoors	North				Indoors			+						
	Indoors			East		Indoors					+				
	Fence		South			More than 6 hours a day					+	+			
	Fence		South	East		More than 6 hours a day			+	+	+			+	+
	Fence		South	East		More than 6 hours a day			+	+		+			
	Balcony banisters		South	East		More than 6 hours a day			+	+		+		+	+
	Fence			East	West	More than 6 hours a day	+	+			+				

ds of	How do you water your living wall?	Who is taking care of your living wall?	Do you have any experience with gardening?	What are your reasons for using a living w							
Beans				It looks nice	It improves air quality	It's unique	It helps educate others	It saves floor/ground space	For growing herbs and vegetables	It adds nature into the city	It reduces the heat in summer
	Grey water system	I am	I'm an experienced gardener	+	+			+			
	Grey water system	I am	I'm a novice gardener	+	+	+					+
	Hand watering	I am	I'm a novice gardener						+		
	Hand watering	My family	I'm a novice gardener	+	+					+	
+	Hand watering	I am	I'm a landscape architect	+	+				+		
	Manually operated drip irrigation	I am	I'm a novice gardener		+		+		+	+	
	Other	My family	I'm a novice gardener	+	+	+	+	+	+		+
	Hand watering	I am	I'm a novice gardener	+				+	+		
	Hand watering	I am	I'm a novice gardener	+		+		+	+		
	Automatic drip irrigation	Students	Other	+	+		+			+	+
	Hand watering	I am	I'm a landscape architect	+	+			+		+	
	Automatic drip irrigation	I am	Other					+		+	
	Hand watering	I am	I'm a novice gardener	+				+			
	Automatic drip irrigation	I am	I'm a novice gardener	+				+			
	Hand watering	My family	I'm an experienced gardener	+	+		+	+	+	+	+
	Automatic drip irrigation	My family	I'm a novice gardener		+				+	+	+
	Automatic drip irrigation	My family	I'm an experienced gardener	+							
	Hand watering	I am	I'm a novice gardener			+				+	
	No water	I am	I'm a novice gardener	+							
	Hand watering	I am	I'm a novice gardener	+		+	+	+		+	
	Hand watering	I am	I'm a novice gardener							+	
	Manually operated drip irrigation	I am	I'm a novice gardener	+				+	+	+	
	Hand watering	I am	I'm an experienced gardener	+		+		+	+		
	Automatic drip irrigation	I am	I'm a novice gardener	+				+			
	Automatic drip irrigation	I am	I'm an experienced gardener						+		
	Manually operated drip irrigation	I am	I'm an experienced gardener	+		+		+			
	Automatic drip irrigation	My family	I'm a novice gardener	+		+				+	
	Automatic drip irrigation	I am	I'm a landscape architect					+	+		
	Hand watering	My family	I'm an experienced gardener	+							
	Hand watering	I am	I'm a novice gardener							+	
	Hand watering	I am	I'm a novice gardener	+							
	Hand watering	My family	I'm a novice gardener	+		+		+			
	Automatic drip irrigation	Gardener/s	I'm a novice gardener	+			+		+	+	
	Hand watering	I am	I'm a novice gardener							+	
+	Automatic drip irrigation	Other	I'm a novice gardener	+	+	+	+	+	+	+	+
	Automatic drip irrigation	I am	I'm a novice gardener	+							
	Grey water system	My family	I'm a professional horticulturist							+	
	Automatic drip irrigation	I am	Other								+
	Hand watering	I am	I'm a novice gardener	+				+	+		

	Automatic drip irrigation	Other	I'm a novice gardener	+	+	+	+	+		+	
	Automatic drip irrigation	Students	I'm a novice gardener	+	+	+	+	+	+	+	+
	Hand watering	Students	I'm a novice gardener		+		+			+	
	Automatic drip irrigation	Gardener/s	I'm a novice gardener	+	+	+		+	+	+	
	Hand watering	I am	I'm a novice gardener								
	Automatic drip irrigation	I am	I'm a novice gardener					+		+	
	Grey water system	Gardener/s	I'm a novice gardener	+		+		+	+	+	
	Hand watering	I am	I'm a novice gardener	+	+		+	+	+	+	
	Hand watering	I am	I'm a novice gardener						+		
	Hand watering	I am	I'm an experienced gardener	+				+	+		
	Hand watering	I am	I'm a novice gardener						+		
	Automatic drip irrigation	Students	I'm a novice gardener	+	+	+	+	+	+		+
	Automatic drip irrigation	I am	I'm an experienced gardener			+					
	Automatic drip irrigation	Other	I'm an experienced gardener	+	+	+	+	+		+	
	Hand watering	I am	I'm a novice gardener					+			+
	Automatic drip irrigation	My family	I'm a novice gardener						+		
	Hand watering	I am	I'm a novice gardener		+			+			
	Automatic drip irrigation	I am	I'm an experienced gardener	+	+	+	+	+	+	+	+
	Automatic drip irrigation	Students	I'm a novice gardener	+	+	+	+	+	+	+	+
	Hand watering	I am	I'm a novice gardener	+							
	Hand watering	I am	I'm a novice gardener	+				+	+		
	Hand watering	Gardener/s	I'm a novice gardener	+	+	+	+				
	Hand watering	I am	I'm an experienced gardener		+						
	Hand watering	I am	I'm an experienced gardener	+			+				
	Hand watering	I am	I'm an experienced gardener	+	+	+	+	+	+	+	+
	Automatic drip irrigation	My family	I'm a novice gardener						+	+	
	Automatic drip irrigation	Students	I'm a novice gardener	+		+	+				

all?	How would you rate your living wall as:								
It's "green"	Energy efficient	Water sensitive	Low embodied energy	Biodiversity enhancer	Urban agriculture facility	Enhancing sense of community	Educational	Relaxing & mood improving	Overall successful
	3	3	5	5	1	1	5	5	4
	3	4	3	3	3	3	3	4	4
	5	3	3	5	5	3	3	5	5
+	3	3	4	3	4	4	3	4	3
+	2	3	3	2	2	2	2	5	3
	4	4	4	4	3	3	5	5	4
+	3	3	3	3	3	3	4	4	3
+	3	4	5	1	4	1	2	4	4
	3	3	4	3	3	3	4	3	4
+	4	3	5	4	5	4	5	5	5
+	1	1	2	5	5	3	4	5	5
	4	4	4	3	5	3	3	5	5
+	1	1	2	3	4	2	2	3	3
+	1	1	3	1	1	1	3	4	4
+	5	5	5	1	4	4	4	4	4
+	5	5	5	5	5	5	5	5	4
	3	5	4	1	1	1	1	5	4
	3	3	4	3	4	4	4	4	4
	2	2	2	1	1	1	1	1	1
+	1	4	1	1	1	1	1	4	4
	2	2	3	4	5	5	5	4	4
+	3	4	4	2	5	3	4	5	4
+	5	3	3	3	5	1	3	5	5
	2	1	2	2	5	4	4	4	4
	5	5	4	4	5	1	5	5	5
+	5	5	5	5	5	5	5	5	5
+	1	4	1	1	1	1	5	5	3
	1	1	4	1	3	1	1	3	3
	1	2	1	1	1	1	1	1	5
	4	2	1	2	5	5	5	5	5
+	1	1	1	1	1	5	5	5	5
	3	4	2	1	5	1	2	4	3
+	1	2	3	1	5	5	5	5	5
	4	4	4	4	5	5	5	5	5
+	2	3	3	3	5	4	5	5	4
	1	4	1	1	1	1	1	5	5
	5	5	5	3	5	3	3	5	5
	4	4	3	3	2	3	4	5	4
+	1	1	1	1	5	1	1	5	4

+	1	4	4	5	5	5	5	4	5
+	1	1	5	5	5	5	5	5	5
+	2	3	4	4	4	2	5	4	4
+	5	2	2	5	5	5	5	5	5
+	5	5	5	4	5	5	5	5	5
	3	3	3	5	4	3	5	3	4
+	5	3	3	4	4	5	3	5	5
	3	3	4	4	5	2	5	5	3
	5	3	5	5	5	1	1	5	5
+	4	4	5	3	5	1	3	4	4
	5	3	4	2	5	1	4	3	4
	1	5	5	4	4	4	4	4	4
	1	1	1	1	1	1	1	5	5
+	3	4	4	2	5	3	4	3	4
+	4	3	3	1	2	1	3	3	3
	4	3	3	3	5	3	4	5	5
+	3	3	3	2	4	2	2	4	3
+	5	2	3	3	2	3	5	5	4
+	4	3	3	2	4	5	5	5	5
	3	3	4	3	3	2	3	3	3
+	3	3	5	4	5	5	5	4	4
+	1	3	1	1	1	5	5	4	4
	1	3	3	5	2	3	2	5	5
+	3	3	2	1	2	2	4	5	3
+	2	2	2	2	4	4	4	5	4
+	4	4	4	3	4	2	3	3	4
+	3	4	3	3	1	5	5	4	4

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